Geophysical investigations in the English Lake District

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GEOPHYSICAL INVESTIGATIONS IN THE ENGLISH LAKE DISTRICT

A thesis presented for the degree of

Doctor of Philosophy

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APPENDICIES

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ABSTRACT

New regional and detailed gravity surveys have been carried out in the Lake District which define the principal anomalies in considerably more detail than previous widely-spaced observations. The physical properties of the Shap and Skiddaw granites have been analysed from geophysical logs recorded in 300 m deep heat-flow boreholes. New density determinations have been made on outcrop samples from over 350 localities in the western and central Lake District. Samples have been classified in terms of their lithology and lithostratigraphy, and representative in-situ densities have been calculated for the principal formations. The gravity and aeromagnetic data have been interpreted, using a combination of modelling and image processing, in order to study the form and evolution of the Lake District granite batholith and structures within the Skiddaw and Borrowdale Volcanic groups.

The modelling studies indicate that Lake District batholith may comprise up to nine separate deep-seated components, and there may be a further five high level intrusions. The Eskdale/Wasdale Granite forms a major component in the western Lake District, and the Shap and Skiddaw granites form separate, steep-sided intrusions on the south-eastern and north-eastern margins of the batholith respectively. Prominent residual gravity anomalies, which coincide approximately with the Scafell, Haweswater and Ulpha synclines of the Borrowdale Volcanic Group, are also tentatively interpreted in terms of separate batholith components, but alternative interpretations in terms of thickened BVG sequences are possible. Further separate components are postulated along the northern side of the batholith and beneath the Haweswater Complex. The Ennerdale Granophyre and Threlkeld Microgranite are modelled as high-level intrusions, in line with previous interpretations, and it is posssible that the Eskdale Granodiorite is also in this category. There is good evidence for a high-level granitic intrusion beneath the Crummock aureole and some evidence for a similar intrusion near Coniston. On a broader scale, the modelling indicates that long wavelength magnetic anomalies are best interpreted in terms of a 'magnetic basement' which represent either a thick layer of pre-Skiddaw Group (magnetic) sedimentary rocks, magnetic crystalline basement, or a combination of both. This 'basement' reaches nearest to the surface in the southern Lake District, deepens northwards beneath the batholith, and approaches nearer to the surface again along the northern margin.

The image processing of the potential field data has revealed three important ENE-trending geophysical lineaments across the Lake District (the Crummock, Ullswater and Southern Borrowdales lineaments). Several prominent, but less extensive, NE-trending lineaments are also visible across the central and western parts of the area. The ENE-trending set appear to divide distinctive tracts within the Skiddaw Group and it seems likely that at least some of the lineaments represent fundamental fractures within the underlying basement which were initiated prior to the Borrowdale volcanism and which influenced the subsequent structural development of the Borrowdale Volcanic Group and the intrusive form of the batholith. It is possible that vertical movement influenced by the pre-existing NE- and ENE-trending lineaments may have initiated the Scafell, Haweswater and Ulpha synclines, and associated anticlines, in the Ordovician, leading to a thicker accumulation of BVG in the synclines and/or the subsequent emplacement of late Ordovician (or early Silurian?) components of the batholith beneath them. Alternatively, it is possible that each was initiated as a volcano-tectonic sag over a separate component of an evolving Ordovician batholith, the position of the batholith components themselves being influenced by earlier structural trends.

The geothermal characteristics of Caledonian-age granites in the Lake District and Eastern Highlands of Scotland have been studied (in collaboration with other workers). The study has led to a re-examination of the relationship between heat flow (q_0) and heat production (A_0) for granites and basement rocks in the UK. The data form four separate clusters on the q_0-A_0 plot; three corresponding to granite batholiths in SW England, northern England and the Eastern Highlands of Scotland, and a fourth to the basement rocks of central England and Wales. A single linear correlation between q_0 and A_0 is no longer tenable, and an explanation of the data is proposed in terms of the crustal structure and thermo-tectonic setting of each area. In the case of the granite batholiths the data reflect the contrasting depth extent and radioelement - depth functions of the intrusions. These parameters in turn are related to the magmatic evolution and emplacement history of each batholith and the nature of the crust into which they were emplaced.

PREFACE

The research described in this thesis was carried out as part of the author's work at the British Geological Survey (BGS, formerly the Institute of Geological Sciences). The work was funded by three separate projects which, between them, provided the opportunity to study the structure of the Lake District area in some detail and to investigate the geothermal characteristics of the Lake District and other British granites. The three projects, and the author's part in each, were as follows:

(1) **Regional gravity survey of the Lake District.** This was carried out during the early 1980s as part of the national coverage. The author acted as party chief for the main part of the survey during 1981 which used helicopter transport to cover the high ground. The data were processed (corrected for terrain effects etc.) during 1982 by vacation students under the supervision of the author. The regional survey provided the basis for the interpretations carried out under the auspices of other projects (below).

(2) **Assessment of hot dry rock (HDR) geothermal prospects in Caledonian granites (1981-84).** This project was carried out jointly with staff of the Open University and Imperial College and was concerned principally with granites in the Lake District and Eastern Highlands of Scotland. The author acted as project coordinator and was responsible for aspects of the research concerned with defining the 3-D form of the Lake District batholith (from the regional gravity data) and the analysis of geophysical logs from heat-flow boreholes. An overall assessment of HDR prospects in the UK and an analysis of the relationship between heat flow and heat production in British granites were carried out jointly by all project members with MKL acting as lead author.

(3) **Lake District regional geology project (1982-present).** This is a multidiscliplinary BGS project in which detailed remapping is being carried out in parallel with geophysical, geochemical and other research with the aim of understanding the 3-D geological structure and tectonic evolution of the region. The author has

been responsible for the geophysical aspects of the programme. This has included a study of physical property variations, the analysis of structural trends from the gravity and aeromagnetic data using image processing techniques, and detailed joint modelling of the potential field data. These studies have built on the earlier modelling and borehole log analysis carried out for the HDR project.

The timing and degree of overlap between these projects make it difficult to describe the research on a project by project basis. The organization of the thesis is, therefore, as follows:

The main body of the thesis (Chapters 1 to 8) describes research concerned specifically with the Lake District, but carried out under the auspices of all three projects. **This work represents research carried out solely or principally by the author. Where others have assisted in surveys, provided information or worked in collaboration with the author, this is clearly indicated in the text.** Appendix 2 contains copies of four publications (some written in collaboration with others) which are given as supplementary material in support of Chapters 1 to 8 (see List of Supporting Material).

As indicated above, research into the relationship between heat flow and heat production in British granites and the overall assessment of HDR prospects (including consideration of the Lake District granites) was carried out jointly by the author and colleagues in BGS, The Open University and Imperial College. This (collaborative) work is described in Appendix 3 which contains copies of three publications giving the background to the HDR research programme and the principal results (see List of Supporting Material).

Chapter 9 of the thesis contains a summary of the results from both aspects of the research (i.e. the investigations in the Lake District and the related geothermal studies).

A number of BGS Open File reports was written during the course of the work. A full list of all publications based on the work described in this thesis, including those submitted as supporting material, is given at Appendix 1.

ACKNOWLEDGEMENTS

The author is deeply indebted to numerous colleagues in BGS and various university departments for geological information, assistance with field surveys, discussion, feed-back and support throughout the course of this work. Particular thanks are due to the following individuals and institutions.

Colleagues in the Regional Geophysics Research Group (BGS) are thanked for their contributions as follows: Ian Smith, Richard Carruthers, Kevin Wilson, Barry Chacksfield and Sarah Kimbell for their part in the ground and airborne regional gravity surveys of the Lake District; Adrian Walker for his invaluable assistance in carrying out the detailed gravity surveys in the western Lake District, for collecting rock samples for physical property determinations and for his help and advice during the author's 'learning curve' on the I^2S equipment; Dr Andrew McDonald for his help with the I^2S; Dr John Busby who developed the gravity/ magnetic modelling program 'Gravmag' which replaced the previous generation of modelling software (written by the author!); Konrad Dabek, Dr Chris Green and Paul Williamson who wrote a number of the computer programs in the Group's software library used during the course of the research; Ian Smith (again) who initiated the digitisation of the UK aeromagnetic data; Keith Rollin for his role in the HDR geothermal project and for numerous discussions on the relationship between heat flow and heat production during the evolution of our various reports and papers.

Colleagues involved in the BGS Lake District project are thanked for their contributions and assistance as follows: Dr Dave Millward and Dr Tony Cooper for patiently explaining the intricacies of Lake District geology, for helping to develop the framework for the analysis of density variations within the Skiddaw and Borrowdale Volcanic groups, for providing samples for physical property determinations and geological information along the model profiles, and for numerous discussions during the course of the modelling; Dr Peter Allen (who initiated the Lake District project), Dr Barry Webb, Brian Young and Dave Lawrence for providing numerous rock samples and geological information; Dr Derek Cooper and the other co-authors for their part in the study of the Crummock Aureole.

Colleagues in BGS, Imperial College and the Open University who were involved in the HDR geothermal project are thanked as follows: Keith Rollin (BGS), Jim Wheildon (IC), Prof Geoff Brown (OU) and Dr Peter Webb (OU) for their part in the project and the development of ideas regarding the relationship between heat flow and heat production in the UK which led to our joint publications. Funding for the HDR project from the Department of Energy is also acknowledged.

The contribution of other individuals in BGS and elsewhere is also acknowledged as follows: Dr Ron Firman (Nottingham University) for inviting me to join him in writing a paper on the influence of the Lake District batholith on subsequent sedimentation and tectonics, and thereby giving me access to his vast pool of knowledge of Lake District geology; Dr Jack Soper (University of Leeds) for numerous stimulating discussions on Lake District geology and, with Dr Tim Pharaoh, for working with me on the interpretation of the gravity and magnetic images of central Britain which helped set the studies in the Lake District in their regional context.

I would also like to thank the Chief Geophysicist of BGS (Dr Richard Haworth), the Head of the Regional Geophysics Research Group (Dr David McCann) and the Chief Geologist (Dr Peter Allen) for their continued support and encouragement during the course of the research and for allocating sufficient time on the Lake District project for me to complete the research. I thank Prof Geoff Brown on two counts: as a colleague (during the HDR research) and as my OU supervisor for his encouragment and helpful suggestions on early drafts of this thesis.

Finally I would like to thank my family for enduring undecorated rooms and numerous other unfinished DIY tasks during the course of writing up this work. I dedicate this thesis to them.

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LIST OF SUPPORTING MATERIAL

Copies of the papers listed below are submitted as supporting material to the thesis (a brief outline of the author's contribution to each is given). Papers S1 to S4 are included at Appendix 2. Papers S5 to S7 are included at Appendix 3.

S1 **Lee, M.K. 1986. A new gravity survey of the Lake District and three-dimensional model of the batholith. Journal of the Geological Society, London, 143, 425-435.**

This paper is based on the work described in Chapter 4 (MKL sole author).

S2 **COOPER, D.C., LEE, M.K., FORTEY, N.J., COOPER, A.H., RUNDLE, C.C., WEBB, B.C. & ALLEN, P.M. 1988. The Crummock Water Aureole: a zone of metasomatism and source of ore metals in the English Lake District. Journal of the Geological Society, London, 145, 523-540.**

This paper is given in support of Chapter 7. It provides details of a mutlidisciplinary study of the Crummock Aureole carried out as part of the BGS Lake District Project. MKL was responsible for the geophysical aspects of the paper (modelling and image processing).

S3 **FIRMAN, R.J. & LEE, M.K. 1986. The age and structure of the concealed England Lake District batholith and its probable influence on subsequent sedimentation, tectonics and mineralisation. In: NESBITT, R.W. & NICHOL, I. (eds) Geology in the real world - the Kingsley Dunham volume. Institution of Mining and Metallurgy, 117-127.**

This paper was initiated by R.J. Firman and relies heavily on his extensive knowledge of Lake District geology. RJF wrote most of the text with contributions from MKL on the geophysical aspects. The paper is included as supporting material for the discussion in Chapter 8 to give background information relating to the age of the batholith and its subsequent influence on the structural development of the Lake District.

S4 **Correspondence in Geological Magazine in discussion of paper S3 and reply by the authors. The following letters are included:**

> **Geological Magazine, 124, 481-484 (1987): Letter from SOPER (The Ordovician batholith of the English Lake District). Letter from WEBB, MILLWARD, JOHNSON, and COOPER (The Ordovician(?) batholith of the English Lake District). Reply to Webb et al. from SOPER, BRANNEY, MATHIESON and DAVIS.**
>
> **Geological Magazine, 124, 585-587 (1987): Reply to the above letters from FIRMAN and LEE (The English Lake District Batholith - Ordovician, Silurian, Devonian or ....?)**
>
> **Geological Magazine, 125, 183 (1988): Further correspondence from MOSELEY.**

Paper S3 provoked considerable discussion. The correspondence is included to provide further background information to the discussions in Chapter 8.

S5 **LEE, M.K. 1986. Hot Dry Rock. In: DOWNING, R.A. and GRAY, D.A. (eds) 'Geothermal Energy: The Potential in the United Kingdom'. HMSO for the British Geological Survey, London, 21-42.**

This paper describes the background to HDR research in the UK and gives details of the collaborative investigation into the HDR geothermal potential of Caledonian granites in the Lake District and Eastern Highlands of Scotland. As well as the author's own work on the interpretation of geophysical logs and gravity modelling in the Lake District (described in Chapters 3 and 4 of the thesis), the paper also describes research carried out by the other members of the team. These are specifically: (a) heat flow measurments carried out by J. Wheildon and his colleagues at Imperial College, (b) research into the heat production and geochemistry of the target granites carried out by G.C. Brown and P.C. Webb at the Open University, and (c) modelling of the Eastern Highlands granites carried out by K.E Rollin (BGS). The paper concludes by describing a re-assessment of the relationship between heat flow and heat production in the UK based on the results of the project. This re-assessment was carried out by all members of the team with MKL acting as co-ordinator and lead author.

S6 **LEE, M.K., BROWN, G.C., WEBB, P.C., WHEILDON, J. and ROLLIN, K.E., 1987. Heat flow, heat production and thermo-tectonic setting in mainland UK. Journal of the Geological Society, London, 144, 35-42.**

S7 **WEBB, P.C., LEE, M.K.and BROWN, G.C. 1987. Heat flow - heat production relationships in the UK and vertical distribution of heat production in granite batholiths. Geophysical Research Letters, 14, 279-282.**

Papers S6 and S7 were based on the results of the HDR study. MKL acted as lead author for S6 and PCW for S7.

CHAPTER 1

INTRODUCTION AND GEOLOGICAL BACKGROUND

1.1 INTRODUCTION

As Bott (1978) noted, 'knowledge of the deep structure of the Lake District is mainly dependent on geophysics, particularly gravity studies'. Consequently, most of the pioneering geophysical research in the area was carried out by Bott (1974 and 1978) who published the first regional-scale gravity survey of the Lake District. This revealed a belt of relatively low Bouguer anomaly values linking the Shap, Skiddaw and Eskdale granites which Bott interpreted in terms of an underlying batholith (Figure 1.1). The interpretation indicated that the major granitic intrusions extend to depths of between 7 and 10 km and that the central part of the Lake District is underlain by granite at relativaly shallow depth.

Bott (1974 & 1978) also suggested that the batholith might be connected via a deep granite ridge beneath the Vale of Eden to the Weardale Granite in the northern Pennines. More recently, however, Collar (1981) has explained the field in the Vale of Eden without recourse to an underlying granite ridge. Since Bott's (1974 & 1978) interpretation, Locke & Brown (1978) have made detailed gravity observations over the roof zone of the Shap Granite and published a model of the upper part of the intrusion.

Compared with the gravity data, the aeromagnetic data from the Lake District have been underexploited. Collar & Patrick (1978) modelled the prominent anomaly over the Eycott Volcanic Group and Locke & Brown (1978) interpreted magnetic data over the Shap Granite but, as

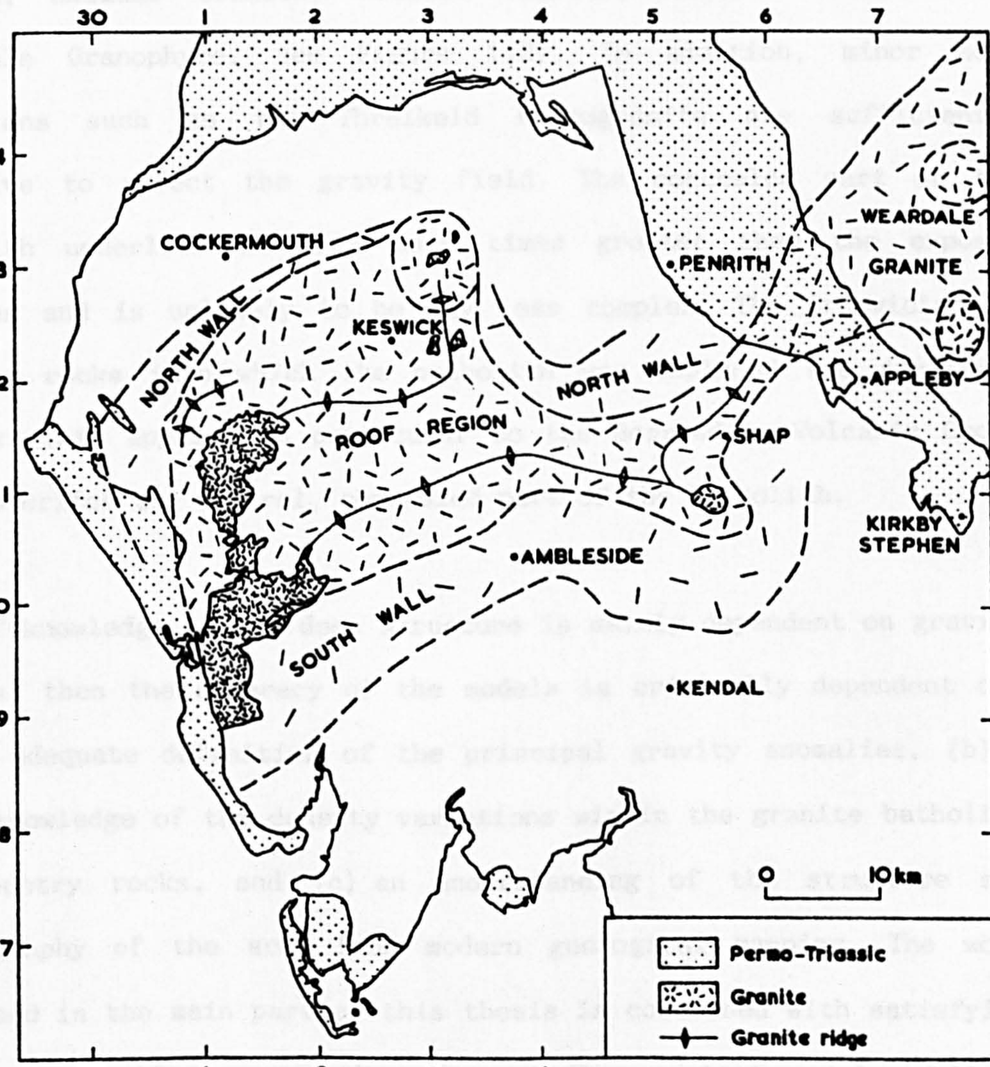


Figure 1.1 Postulated form of the Lake District batholith from Bott (1974 & 1978)

far as the author is aware, little joint gravity and magnetic modelling has been carried out.

The Lake District granitic batholith is a composite body with at least five distinct, major, acid intrusions recognized at outcrop (Shap Granite, Skiddaw Granite, Eskdale Granite, Eskdale Granodiorite, Ennerdale Granophyre, see Figure 1.2). In addition, minor acid intrusions such as the Threlkeld Microgranite are sufficiently extensive to affect the gravity field. The concealed part of the batholith underlies an area many times greater than the exposed portions and is unlikely to be any less complex. The Ordovician to Silurian rocks into which the batholith was emplaced are similarly complex. This applies in particular to the Borrowdale Volcanic Group which overlies the central, concealed part of the batholith.

If knowledge of the deep structure is mainly dependent on gravity studies, then the accuracy of the models is critically dependent on: (a) an adequate definition of the principal gravity anomalies, (b) a sound knowledge of the density variations within the granite batholith and country rocks, and (c) an understanding of the structure and stratigraphy of the area from modern geological mapping. The work described in the main part of this thesis is concerned with satisfying the first two of these requirements and then analysing and modelling both the gravity and aeromagnetic data against the geological control provided by recent mapping. The principal objectives of the work were: (a) to develop a better understanding of the form of the composite batholith, (b) to investigate structures within the Skiddaw and Borrowdale Volcanic groups in relation to both the tectonic evolution

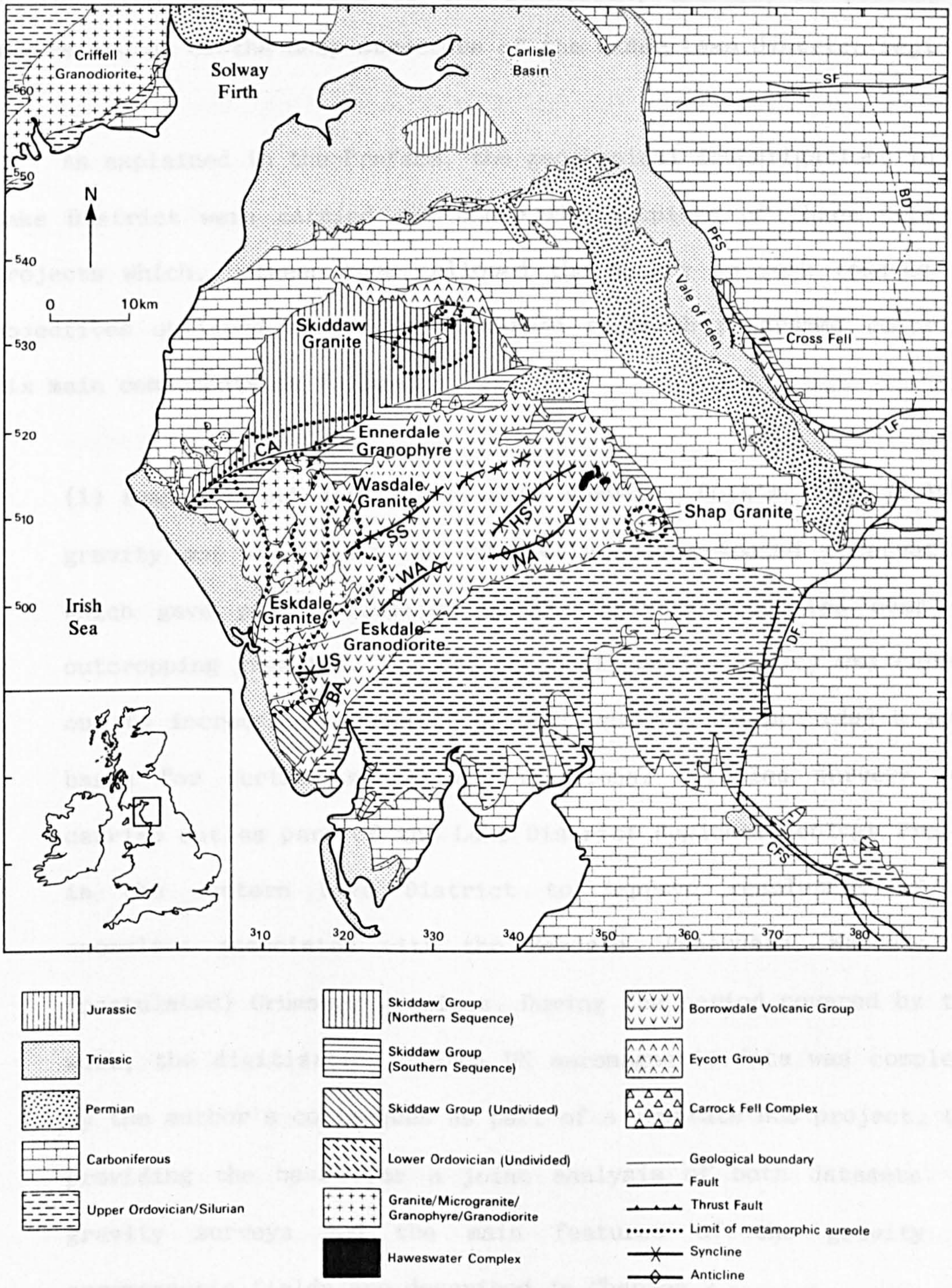


Figure 1.2 Geological map of the Lake District region. BA = Black Combe Anticline, BD = Burtreeford Disturbance, CA = Crummock Aureole, CFS = Craven Fault System, HS = Haweswater Syncline, LF = Lunedale Fault, NA = Nan Bield Anticline, PFS = Pennine Fault System, SF = Stublick Fault, SS = Scafell Syncline, US = Ulpha Syncline, WA = Wrynose Anticline

of the area and the form of the batholith, and (c) to develop an understanding of the deep structure of the wider Lake District region.

As explained in the Preface, the geophysical investigations in the Lake District were carried out under the auspices of three separate projects which, between them, allowed the author to work towards the objectives outlined above. The combined research programme comprised six main components as follows:

(1) **Regional and detailed gravity surveys.** Bott's (1974 & 1978) gravity map was based on relatively widely-spaced observations which gave poor definition of the gravity anomalies over the outcropping granites. The BGS regional gravity survey was carried out to increase the density of observations and provided a sound basis for further modelling. Additional detailed surveys were carried out as part of the Lake District Regional Geology Project in the western Lake District to improve resolution of the anomalies associated with the Eskdale, Ennerdale, Wasdale and (postulated) Crummock granites. During the period covered by this work, the digitization of the UK aeromagnetic data was completed by the author's colleagues as part of a separate BGS project, thus providing the basis for a joint analysis of both datasets. The gravity surveys and the main features of the gravity and aeromagnetic fields are described in Chapter 2.

(2) **Analysis of the physical properties of the Shap and Skiddaw granites from geophysical borehole logs.** Heat flow boreholes approximately 300 m deep were drilled into the Shap and Skiddaw granites (and 4 boreholes in the Eastern Highlands of Scotland)

for the HDR project. A suite of geophysical logs was run in each borehole to monitor changes in lithology and investigate the physical and geothermal properties of the rocks. The analysis techniques are described in Chapter 3, together with the results for the Shap and Skiddaw granites (the results for the Scottish granites are included in Appendix 5 for the sake of completeness).

(3) Generalized 3-D gravity interpretation of the Lake District batholith. The objective of this part of the work was to define the general 3-D form of the Lake District batholith, both in order to improve understanding of the deep structure of the region and provide a basis for subsequent heat flow modelling by the Imperial College group (see Preface and Appendix 3). Attention was focussed mainly on the Shap and Skiddaw granites, on which the heat flow boreholes were sited. The modelling was based on the regional gravity data and was carried out prior to the detailed surveys in the western Lake District. This work is described in Chapter 4.

(4) Additional rock physical property measurements and detailed analysis of density variations. Both Bott's (1974 & 1978) models and the 3-D interpretation referred to above were based on relatively simplified density distributions for both the batholith and cover sequences. Bott recognized that lateral density variations within the batholith were required to model the shape of the negative gravity anomaly but he assumed a single (background) density for the Skiddaw and Borrowdale Volcanic groups. Likewise, the 3-D interpretation assumed a simple density distribution within the batholith and a single background density. It became clear that a better understanding of density variations in the Lake District was required in order to delineate the component parts of the batholith and investigate important structures within the Ordovician basement. New density determinations were made on samples from over 350 localities and the results analysed in detail to define density contrasts between the exposed granites and variations within the Skiddaw and Borrowdale Volcanic groups. This work is described in Chapter 5.

(5) The analysis of structural information from the gravity and aeromagnetic datasets using image processing techniques. The objective of this part of the work was to develop the use of image processing techniques to analyse anomalies and structural trends relating to: (a) structures within the Skiddaw and Borrowdale Volcanic groups, (b) the form and composition of the batholith, and (c) the tectonic evolution of the Lake District area. This work is described in Chapter 6.

(6) Detailed gravity and magnetic modelling. Chapter 7 describes detailed joint gravity/ magnetic modelling to examine structures on both local and regional scales using the information provided by the earlier studies (i.e. the improved gravity coverage from the detailed surveys in the western Lake District, the improved physical property database, the tighter geological control provided by the recent mapping, and the additional structural information provided by the image analysis).

The results and conclusions of this work, relating specifically to the nature of the Lake District batholith and the tectonic evolution of the area are discussed in Chapter 8. As explained in the preface, the collaborative work pertaining to the geothermal characteristics of Caledonian granites in general (but including consideration of the Lake District granites) is described in Appendix 3. The results and achievements of all the work (relating both to the Lake District and the broader geothermal studies) are summarised in Chapter 9.

1.2 THE GEOLOGY OF THE LAKE DISTRICT

The geology of the Lake District has been described by numerous authors and a good summary of the situation as understood by the mid 1970's is given in the collection of papers edited by Moseley (1978). In recent years, significant advances have been made in the course of remapping by BGS and others, and the following account concentrates on these. The new information is incorporated into a map of the central part of the area (Figure 1.3) which should be used in conjunction with the regional map shown in Figure 1.2.

1.2.1 The Skiddaw and Eycott groups

The Ordovician lithostratigraphy is summarized in Figure 1.4 (from Cooper et al. 1988). The oldest rocks exposed in the Lake District are the turbidites of the Skiddaw Group which comprise a thick sequence of mudstone, siltstone and sandstone of Tremadoc to Llanvirn age (Wadge et al. 1972, Moseley 1984 and Molyneux & Rushton 1985). They are generally considered to be fore-arc deposits laid down on the southern margin of Iapetus. The base of the group is not seen and the underlying basement is unknown, although the WINCH and NEC seismic data (off-shore to the west and east respectively) indicate the presence of continental basement, possibly of arc affinity, below a depth of about 10 km (see Section 1.4). The upper part of the group is contemporaneous with volcanic rocks of the Eycott Volcanic Group (Figure 1.4 and below).

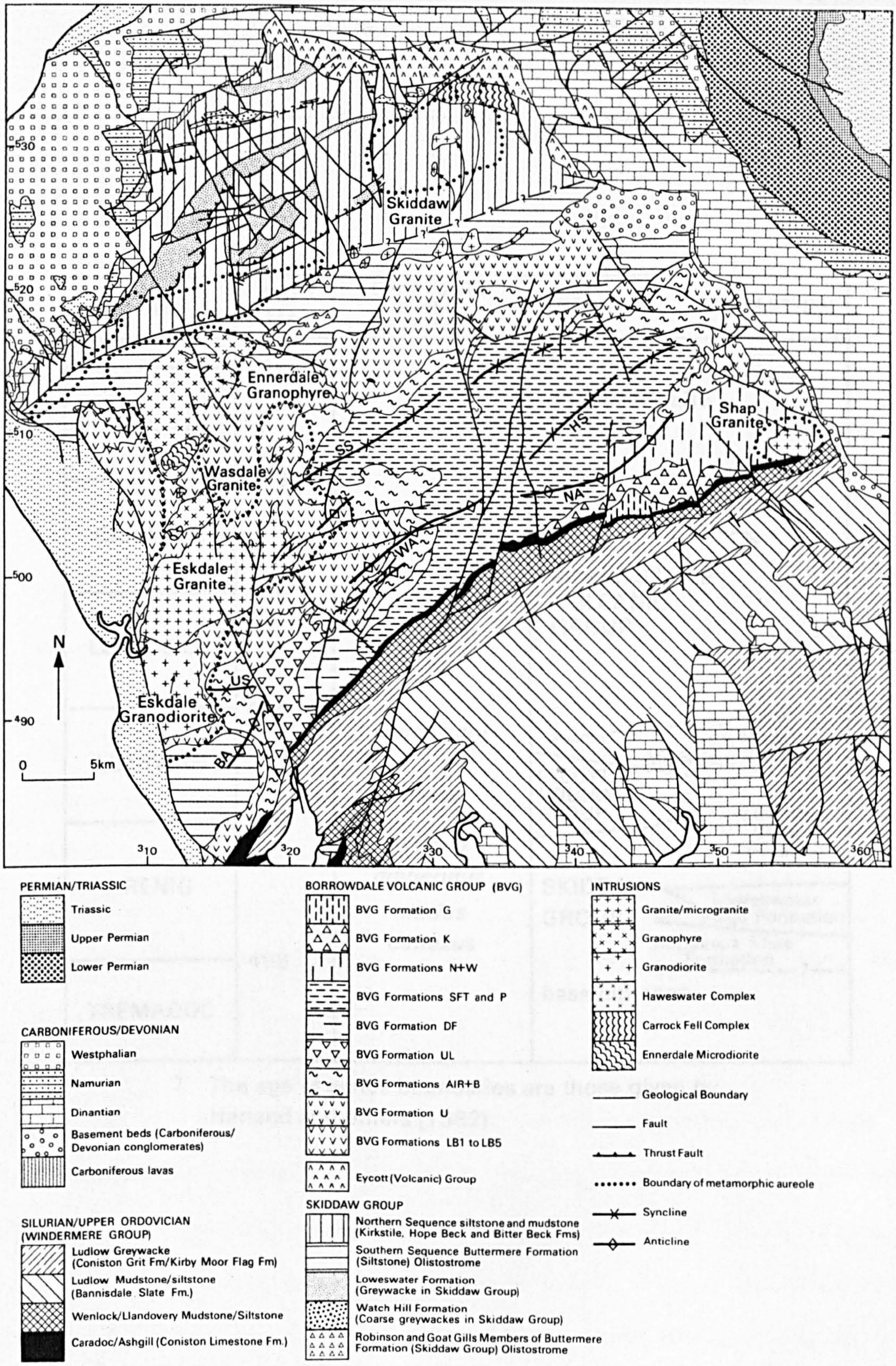
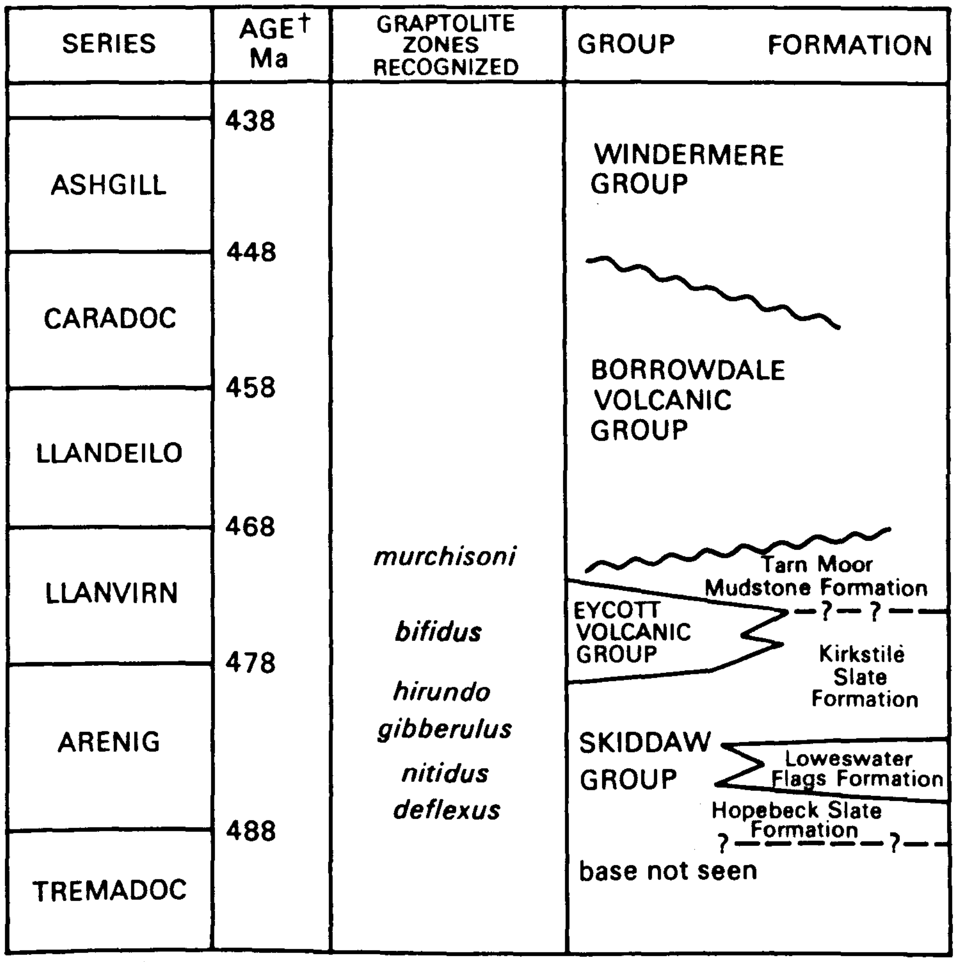


Figure 1.3 **Geological map of the central Lake District. CA = Crummock Aureole, SS = Scafell Syncline, HS = Haweswater Syncline, US = Ulpha Syncline, WA = Wrynose Anticline, NA = Nan Bield Anticline, BA = Black Combe Anticline.**



† The age of series boundaries are those given by Harland and others (1982).

Figure 1.4 Ordovician lithostratigraphy in the Lake District (from Cooper et al. 1988, adapted from Moseley 1984).

A lack of distinctive marker horizons and the structural complexity of the group have resulted in numerous changes in the stratigraphical nomenclature and ordering of formations during the past hundred years. Jackson (1978) divided the Skiddaw Group in the main inlier into four formations (Figure 1.5). These are:

(1) The Latterbarrow Sandstone; exposed only over a relatively small area in the southwestern part of the inlier (not shown on Figure 1.5), up to 400m thick.

(2) The Kirk Stile Slates; mainly dark silty mudstones approximately 1km thick.

(3) The Loweswater Flags; a sequence of alternating grey flaggy sandstones and grey or greenish mudstones approximately 1200m thick.

(4) The Hope Beck Slates; mainly dark silty mudstones, base not seen.

Jackson's (1978) division has been widely accepted and forms a useful basis for examining possible density variations within the Skiddaw Group (see Chapter 5). However, as a result of recent mapping by BGS in the central part of the inlier, A.H. Cooper and B.C. Webb (BGS, pers. comm.) have proposed a new stratigraphy shown in Figure 1.6 (a revised geological map of the main inlier based on this stratigraphy is incorporated into Figure 1.3). The Causey Pike Thrust, which forms part of the southern margin of the Crummock aureole and is associated with a major ENE-trending geophysical lineament (Chapter 6 and Cooper

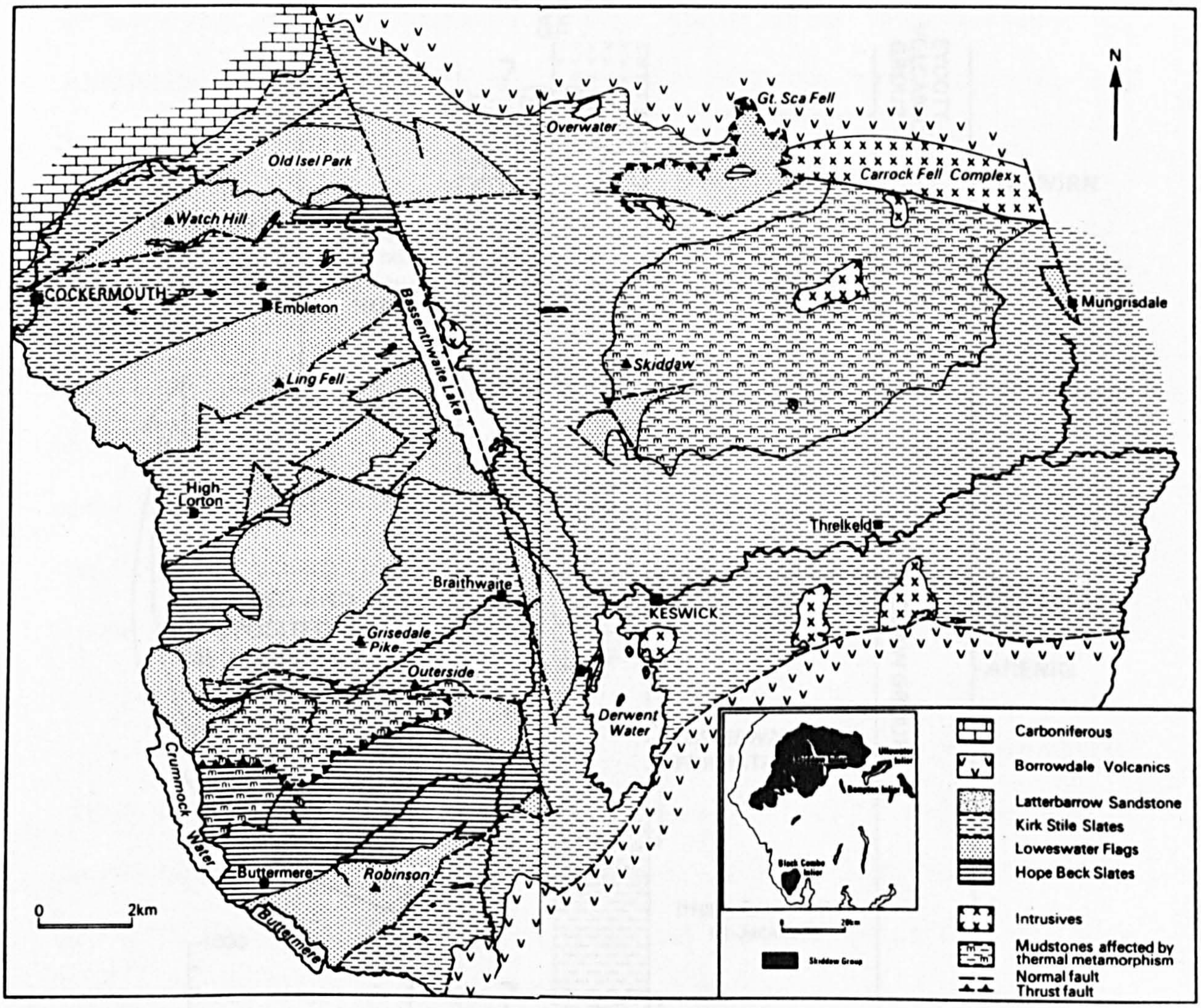


Figure 1.5 Distribution of formations in the eastern part of the Skiddaw Group inlier as proposed by Jackson (1978).

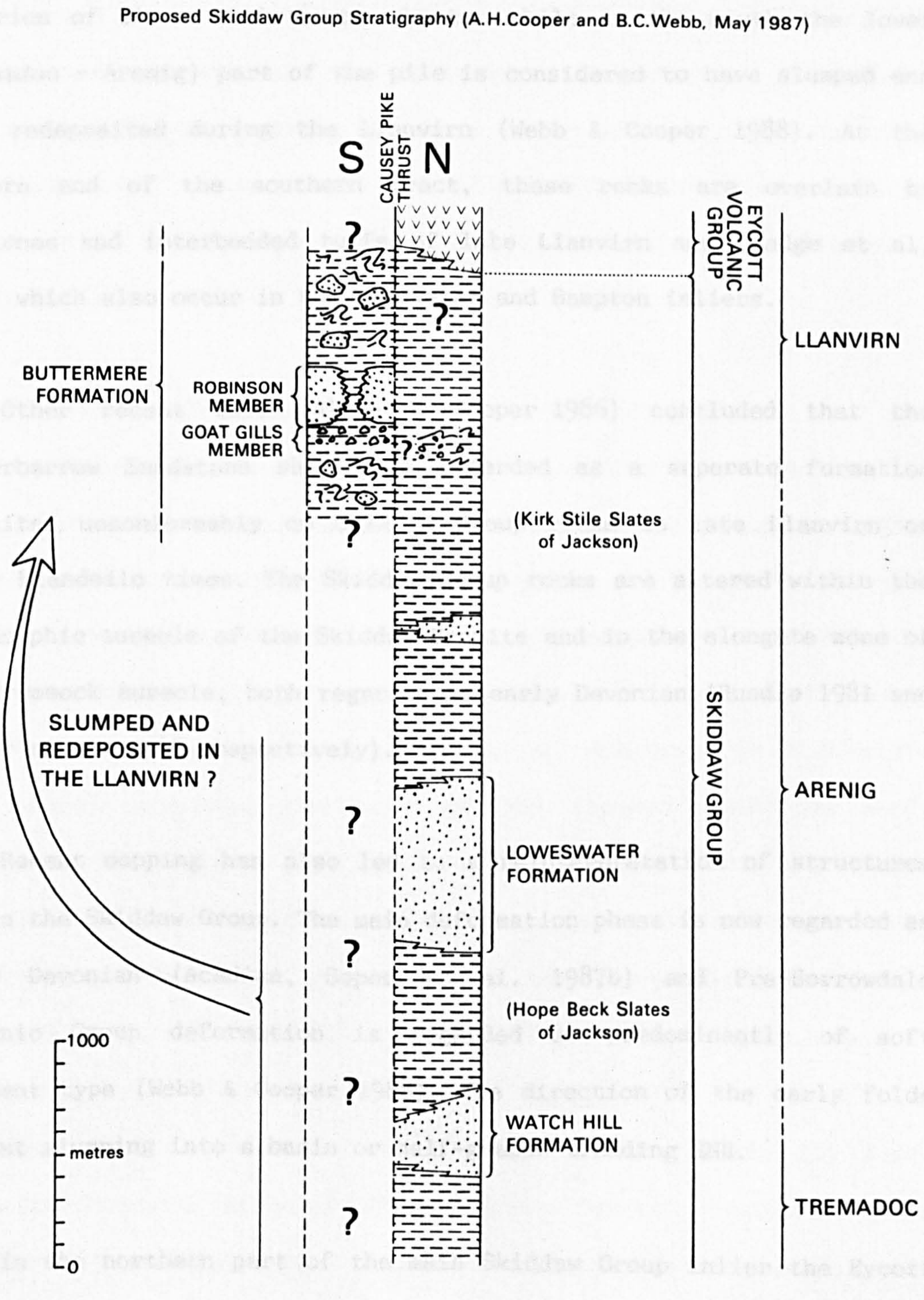


Figure 1.6 **Proposed stratigraphy for the Skiddaw Group by A.H. Cooper and B.C. Webb (pers. comm.). See text for details.**

et al. 1988), is recognized geologically as dividing two distinct tracts. To the north, the sequence is severely folded and faulted into a series of blocks and thrust sheets, while to the south the lower (Tremadoc - Arenig) part of the pile is considered to have slumped and been redeposited during the Llanvirn (Webb & Cooper 1988). At the eastern end of the southern tract, these rocks are overlain by mudstones and interbedded tuffs of late Llanvirn age (Wadge et al. 1972) which also occur in the Ullswater and Bampton inliers.

Other recent work (Allen & Cooper 1986) concluded that the Latterbarrow Sandstone should be regarded as a separate formation deposited unconformably on Skiddaw Group rocks in late Llanvirn or early Llandeilo times. The Skiddaw Group rocks are altered within the metamorphic aureole of the Skiddaw Granite and in the elongate zone of the Crummock aureole, both regarded as early Devonian (Rundle 1981 and Cooper et al. 1988 respectively).

Recent mapping has also led to a reinterpretation of structures within the Skiddaw Group. The main deformation phase is now regarded as early Devonian (Acadian, Soper et al. 1987b) and Pre-Borrowdale Volcanic Group deformation is regarded as predominantly of soft sediment type (Webb & Cooper 1988). The direction of the early folds suggest slumping into a basin or half-graben trending ENE.

In the northern part of the main Skiddaw Group inlier the Eycott Volcanic Group conformably overlies (and may locally intercalate into) Skiddaw Group mudstones of early Llanvirn age (Downie & Soper 1972). The Eycott volcanics comprise about 2500m of basalt and basaltic andesite with some acid lavas and tuffs (Eastwood et al. 1968). In addition to the main outcrop on the northern limb of the Lake District anticline, where they dip steeply to the north, Eycott-type lavas occur at Eycott Hill, in the Greystoke Park inlier and in a small patch in the northern part of the Cross Fell inlier (Figure 1.2). The Eycott Group represents the earliest volcanism in the Lake District. The lavas are transitional between tholeiitic and calc-alkaline and are generally considered to have evolved close to a continental margin (Fitton & Hughes 1970).

1.2.2 The Borrowdale Volcanic Group

The Borrowdale Volcanic Group (BVG) unconformably overlies the Skiddaw Group in the central Lake District. As the youngest Skiddaw Group sediments are late Llanvirn (Wadge et al. 1972) and the post-BVG sequence extends down to the Longvillian (Ingham & McNamara 1978), the Borrowdale Volcanic Group has generally been regarded as of Llandeilo age. However, recent micropalaeontological evidence (S.G. Molyneux pers. comm.) suggests that much of the sequence could be early Caradocian. The volcanic pile is up to 6km thick and shows considerable compositional diversity, comprising basaltic to rhyolitic lavas, welded ignimbrites, primary and reworked tuff and coarse to fine breccia (Millward et al. 1978, Moseley & Millward 1982, Millward pers.comm.).

Two principal phases of activity are distinguished: (1) Early volcanism dominated by basalt to andesite flows and sills with minor interbedded primary and reworked pyroclastic deposits; and (2) deposition of volcanogenic epiclastic rocks interbedded with widespread intermediate to acid ignimbrites, many of which are voluminous and associated with volcano-tectonic faulting. This broad picture disguises numerous variations and complexities which make correlating the sequences in different parts of the Lake District a difficult procedure (Millward et al. 1978, Moseley & Millward 1982).

The volcanic rocks are currently being re-mapped as part of the BGS Lake District Project with the aim of erecting a unified stratigraphy for the Borrowdale Volcanic Group. The sequences shown in Figure 1.7 are based on those given by Moseley & Millward (1982) with modifications by Millward (pers. comm.) to take account of recent mapping. For the purpose of calculating representative density values and analysing the gravity field (Chapters 5 6 and 7), the sequence was divided into a set of 'composite formations', each with a characteristic mix of lithologies (these are indicated by the codes on Figure 1.7 and are shown on the geological map in Figure 1.3). It must be stressed that the 'composite formations' were erected solely for the purpose of the density analysis and bear no necessary resemblance to any lithostratigraphic formations (and names) that may be used in the final unified stratigraphy for the BVG. New mapping has been confined mainly to the SW Lake District - in other areas the formation names shown are based on outdated maps and the correlations indicated should be treated with caution.

As in the Skiddaw Group, a reappraisal of the significance of structures within the Borrowdale Volcanic Group has accompanied the recent mapping. Branney & Soper (1988) have shown that much of the pre-Windermere Group deformation is volcano-tectonic in origin, resulting from periodic caldera collapse. These authors suggest that large scale folds such as the Ulpha and Scafell synclines are not related to Ordovician compression as previously thought (Soper & Newman 1974), but are compatible with bending associated with the foundering

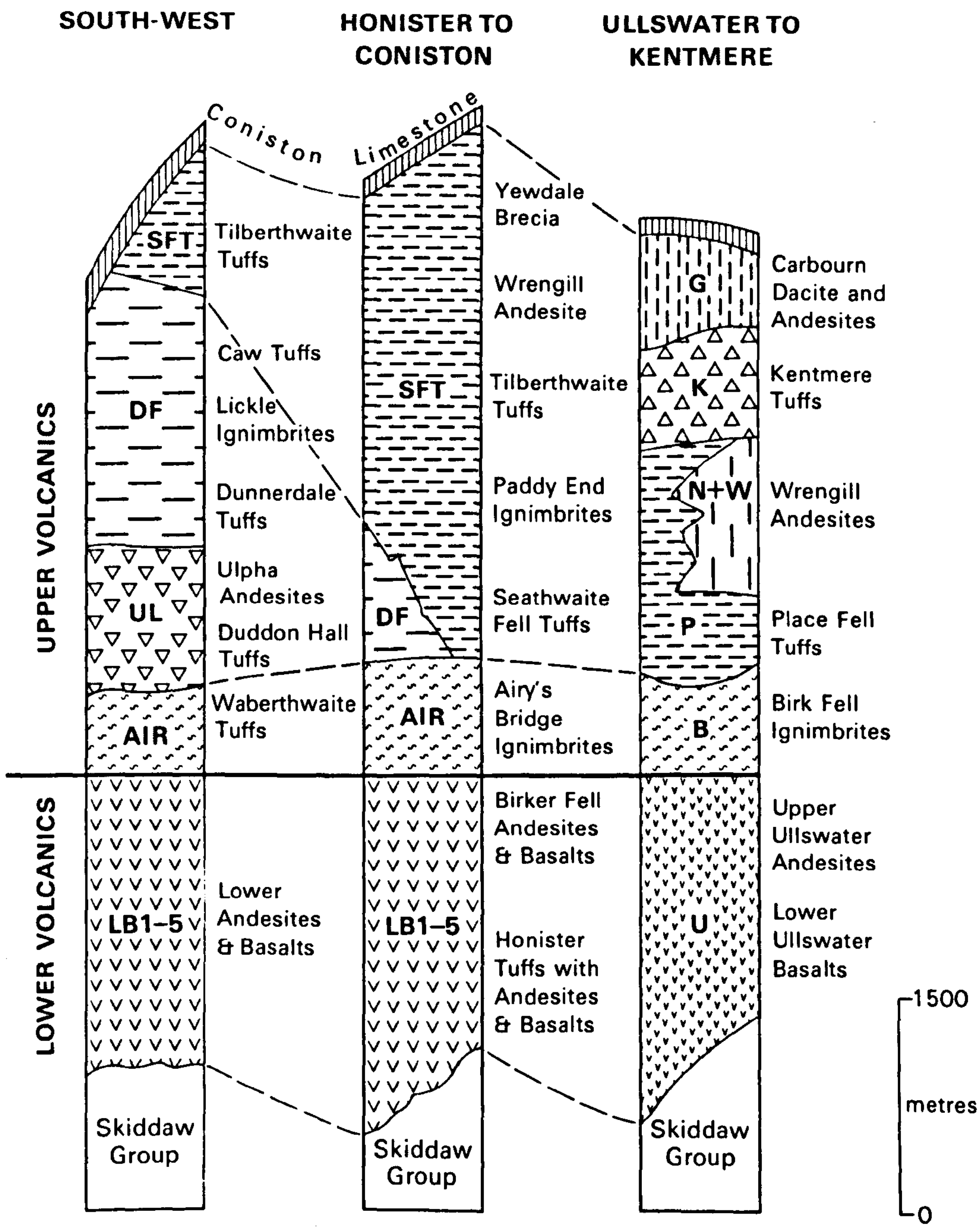


Figure 1.7 Comparative sections for the Borrowdale Volcanic Group after Moseley and Millward (1982) with further modifications by Millward (pers. comm). Letter codes indicate the 'composite formations' erected for the purpose of calculating representative density values (see text).

of the volcanic pile. Similarly, a re-examination of evidence relating to the Nan Bield and Wrynose anticlines led them to conclude that these too were not initiated by compression in the Ordovician. The BVG was emplaced largely in a subaerial environment and must have been associated with crustal subsidence for the volcanic edifice to have survived subsequent erosion (Branney 1988, Branney & Soper 1988). In the SW Lake District, the thickness and sedimentology of Phase 2 volcanics suggest deposition within basins that are thought to have been fault controlled (Millward & Johnson in prep.).

The lack of evidence for Ordovician compression in either the Skiddaw or Borrowdale Volcanic Groups is taken by Soper et al. (1987b) and Branney & Soper (1988) as evidence against an Ordovician closure of Iapetus, the regional Emsian/Acadian deformation marking the final closure of Iapetus (docking of Eastern Avalonia, see Section 1.3). Branney & Soper (1988) also interpreted the pre-BVG unconformity in terms of regional uplift prior to volcanism and the post-BVG (pre-Windermere Group) unconformity as due to 'erosion and overstep of a collapsed subaerial volcanic edifice, without regional compression and uplift'. The influence of the batholith on Lake District deformation and subsidence was examined by Firman & Lee (1986) and is further discussed in Chapters 6, 7 and 8.

1.2.3 The Windermere Group

Upper Ordovician (Ashgill) sedimentary rocks (the Coniston Limestone Formation) progressively overstep the eroded Borrowdale volcanic rocks and are overlain by a thick (5 km) pile of Silurian mudstone, siltstone and greywacke now preserved on the southern limb of the Lake District anticline. The earliest known post-BVG sediments occur in a small faulted outlier in the northern Lake District and within the Cross Fell inlier, and are of mid Caradoc (Longvillian) age (Ingham & McNamara 1978). The name Windermere Group was introduced by Moseley (1984) to cover the entire sequence of Upper Ordovician and Silurian rocks. The area around Kentmere and Crook has recently been remapped by Lawrence et al. (1986) and their generalized vertical section is shown in Figure 1.8. The sequence for the southern Lake District is summarized in Table 1.1.

The depositional environment evolved from shallow-sea, influenced by local block faulting, during the Ashgill and early Llandovery, to that of a deepening basin, so that the Brathay Flags accumulated in a distal turbidite environment (Lawrence et al. 1986, Ingham & McNamara 1978, Rickards 1978). The first influx of northerly derived coarse turbidites (the Lower Coldwell Beds) occurred in the Wenlock (Furness et al. 1967) and is generally assumed to indicate the narrowing or closure of Iapetus (see discussion in Section 1.3). The composition of greywackes in the overlying Coniston Grit Formation suggests that, while an uplifted Southern Uplands may have provided a northwesterly source for much of the material, at least part of the source region may have been a recently emergent volcanic/granitic terrain to the northwest (the Lake District ?, Lawrence et al. 1986). The Bannisdale Slate Formation marks a return to a distal turbidite environment in a subsiding basin. The overlying Underbarrow Flag and Kirby Moor Flag formations were deposited in a tectonically active, shallowing, basinal environment (Lawrence et al. 1986). Folding and cleavage within the Upper Ordovician-Silurian sequence is almost entirely due to the Acadian (Emsian) deformation (Lawrence et al. 1986, Soper et al. 1987b).

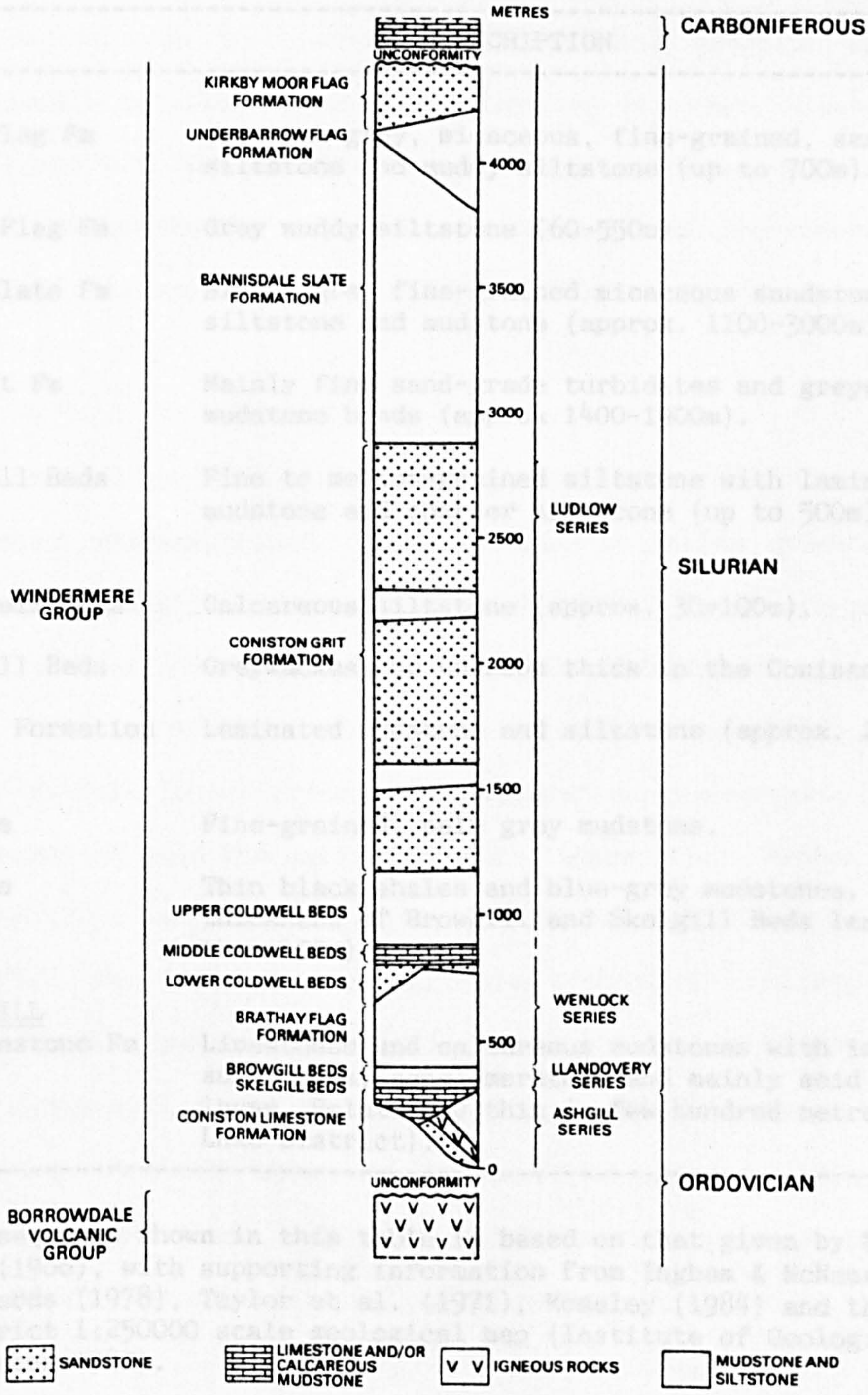


Figure 1.8 Stratigraphy for the Windermere Group (from Lawrence et al. 1986, Figure 2).

TABLE 1.1 Upper Ordovician and Silurian sequence (Windermere Group) in the southern Lake District.

FORMATION	DESCRIPTION
LUDLOW	
Kirby Moor Flag Fm	Greenish grey, micaceous, fine-grained, sandstone, siltstone and muddy siltstone (up to 700m).
Underbarrow Flag Fm	Grey muddy siltstone (60-550m).
Bannisdale Slate Fm	Bluish grey fine-grained micaceous sandstone, siltstone and mudstone (approx. 1100-3000m).
Coniston Grit Fm	Mainly fine sand-grade turbidites and greywackes with mudstone bands (approx 1400-1900m).
Upper Coldwell Beds	Fine to medium-grained siltstone with laminae of mudstone and coarser siltstone (up to 500m).
WENLOCK	
Middle Coldwell Beds	Calcareous siltstone (approx. 30-100m).
Lower Coldwell Beds	Greywackes, up to 200m thick in the Coniston area.
Brathay Flag Formation	Laminated mudstone and siltstone (approx. 200-400m).
LLANDOVERY	
Browgill Beds	Fine-grained, pale grey mudstone.
Skelgill Beds	Thin black shales and blue-grey mudstones. (Total thickness of Browgill and Skelgill Beds less than 100m).
CARADOC/ASHGILL	
Coniston Limestone Fm	Limestones and calcareous mudstones with intercalated sandstones, conglomerates, and mainly acid tuffs and lavas. Relatively thin (a few hundred metres) in the Lake District).

NOTE: The sequence shown in this table is based on that given by Lawrence et al. (1986), with supporting information from Ingham & McNamara (1978), Rickards (1978), Taylor et al. (1971), Moseley (1984) and the Lake District 1:250000 scale geological map (Institute of Geological Sciences 1982).

1.2.4 Intrusions

The Lake District granitic batholith is a composite body with five distinct, major, acid intrusions at outcrop (Shap Granite, Skiddaw Granite, Eskdale Granite, Eskdale Granodiorite, Ennerdale Granophyre, Figures 1.2 and 1.3) and additional minor acid intrusions such as the Threlkeld Microgranite. The concealed part of the batholith underlies a large area of outcropping Skiddaw Group and Borrowdale Volcanic Group rocks.

The principal varieties of Eskdale Granite recognized at outcrop are medium to coarse-grained, pink, perthite-muscovite granite and subordinate microgranite (Firman 1978, Young 1985a). The coarse-grained granite exposed at Wasdale Head (the Wasdale Granite) is generally considered to be part of the same intrusion (e.g. Firman 1978, Ansari 1983). The Eskdale Granodiorite is recognized as a petrogenetically distinct intrusion from the Eskdale Granite (Ansari 1983, Firman 1978) and limited field evidence suggests that it may be slightly older (Young 1985b). The bulk of the Ennerdale Granophyre consists of a fine-grained, pink, quartz-alkali feldspar rock (Firman 1978). It crops out over a large area around Ennerdale and in a smaller outcrop to the north of the Eskdale Granite (Figure 1.3). Separate diorites, xenolithic and hybrid rocks (e.g. a microdiorite variety, known locally as 'Needle Rock') are common within the intrusion (Firman 1978).

The Shap Granite consists mostly of a coarse, pink, porphyritic adamellite (Grantham 1928). Small enclaves of grey granite are common and possibly represent an earlier crystalline phase of the intrusion (e.g. Firman 1978). The Skiddaw Granite is exposed in three small outcrops in the northern part of the Lake District (Figure 1.3) but the roof zone underlies a much larger area as evidenced by the extent of the metamorphic aureole and gravity modelling (Eastwood et al. 1968, Bott 1974 and 1978, this work). The central (Caldew) outcrop consists mainly of grey biotite-granite which is severely weathered and crumbly in places. The Grainsgill outcrop is composed mainly of white biotite-granite exhibiting various stages of greisenization (Firman 1978, Webb & Brown 1984).

Minor intrusions in the Lake District range in composition from basic to acid. Those considered important geophysically include the Threlkeld Microgranite and the Carrock Fell Complex (Figure 1.3). The former is considered to be in the form of an irregular laccolith intruded into the Skiddaw Slates close to the overlying Borrowdale volcanics (Firman 1978). The Carrock Fell Complex comprises gabbro, granophyre and diabase intruded discordantly along the junction between the Skiddaw and Eycott Volcanic groups on the northern margin of the Lake District (Firman 1978).

The main batholith building phase of the Lake District was commonly assumed to be end Silurian - early Devonian (i.e. contemporaneous with the emplacement of the Weardale and Wensleydale granites) until radiometric age data suggested that there were (at least) two phases of major intrusive activity. The Threlkeld Microgranite has been dated as 438 +/-6 (Rundle 1981) and is considered to be comagmatic with the Borrowdale volcanics (Wadge et al. 1974). The Eskdale Granite, Eskdale Granodiorite and the Ennerdale Granophyre have been dated at 429 +/-4 Ma, 428 +/-71 Ma and 420 +/-4 Ma respectively (Rundle 1979) and are now considered to represent the first episode of major intrusive activity. The second major intrusive phase occurred after the final closure of the Iapetus ocean and is represented at outcrop by the Shap (393 +/-3 Ma, Wadge et al. 1978) and Skiddaw (399 +/-8 Ma, Rundle 1981) granites.

Whether the bulk of the batholith at depth is of Ordovician, Silurian or early Devonian age has been the subject of considerable controversy in recent years. On the basis of the 3-D gravity model described in Chapter 4, the present author has argued that the concealed batholith beneath the central Lake District appears to be in geophysical continuity with the Eskdale Granite whereas the later Shap and Skiddaw intrusions formed steep-sided plutons on the margin of the main batholith (Lee 1984a and 1986). Firman & Lee (1986 and 1987) reviewed other geological information and concluded that the evidence was in favour of a large component of the batholith being emplaced in the late Ordovician, before the Caradoc-Ashgill trangression. This view was supported by Soper et al. (1987a) but it implies that the Rb/Sr ages for the Eskdale and Ennerdale intrusions must have been reset as they correlate with the late Llandovery - Wenlock period on most recent timescales (eg. McKerrow et al. 1985). Webb et al. (1987) argued that the radiometric dates record the true emplacement ages which (on the timescale of McKerrow et al.) would have been during the Silurian basin deepening episode, but before the onset of the most rapid subsidence in the Wenlock-Ludlow. In contrast, O'Brien et al. (1985) argued that the bulk of the concealed batholith, including that beneath the Eskdale outcrop, must be a high heat production granite of early Devonian age to account for the high heat flow in the Lake District area. In fact, while above average heat flow values have been recorded on the (early Devonian) Shap and Skiddaw granites (see Appendix 3) no heat flow measurements have been made in the central and western Lake District to support this contention. These arguments are reviewed in Chapter 8 in the light of the most recent geophysical interpretations.

1.2.5 Devonian, Carboniferous and Permo-Triassic

After a period of uplift related to the early Devonian deformation, the first known deposit is the Mell Fell Conglomerate, of presumed Devonian age (Capewell 1955, Wadge 1978). The sequence is up to 1500 m thick and comprises a lower group of greywacke - cobble-conglomerate which matches the Ludlow rocks of the southern Lake District (but were probably not derived from them, Capewell 1955). These are overlain by finer conglomerate and coarse sandstone with a mixed assemblage of derived pebbles.

The subsequent pattern of sedimentation was influenced to a large extent by basement structures formed during Ordovician and Silurian times. During the Dinantian, seas gradually advanced across the Lake District area. This, together with the northern Pennines (Alston and Askrigg blocks) formed relatively stable massifs underpinned by granite, while thick sedimentary sequences accumulated during the Carboniferous, Permian and Triasic in the surrounding and intervening basins (the Solway Basin, Northumberland Trough, Craven Basin, Stainmore Trough, Vale of Eden, Carlisle Basin and Irish Sea Basin). Unlike the Ordovician rocks, recent mapping has not led to major revisions of the sedimentary sequence or tectonic history. Detailed accounts of the Carboniferous, Permian and Triassic rocks around the Lake District are given by Mitchell et al. (1978) and Arthurton et al. (1978) and are not repeated here. The sequences are summarized in Figures 1.9 and 1.10, and relevant details are given below where they affect the geophysical models.

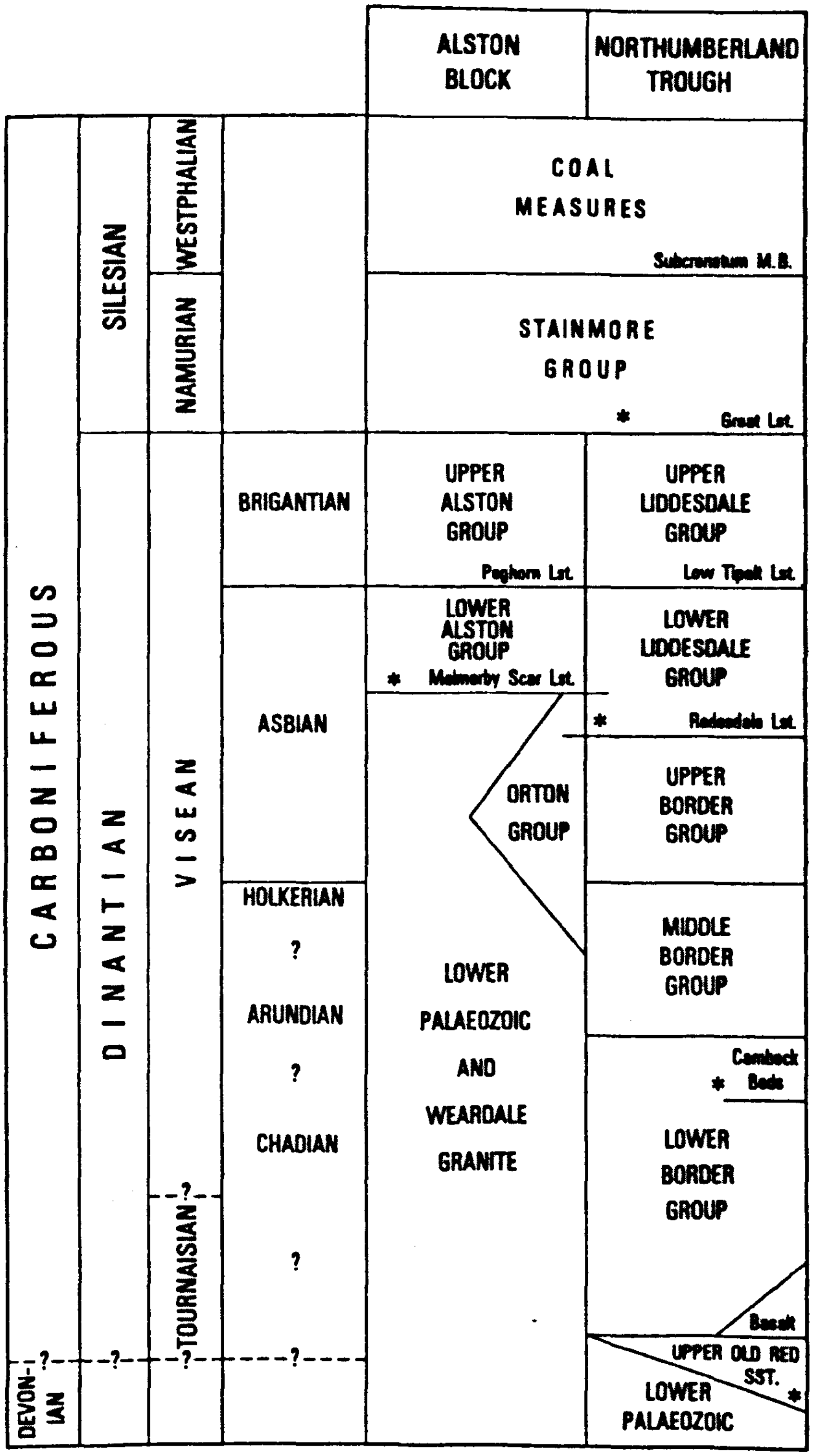


Figure 1.9 Carboniferous succession in north-east England (from Kimbell et al. 1989).

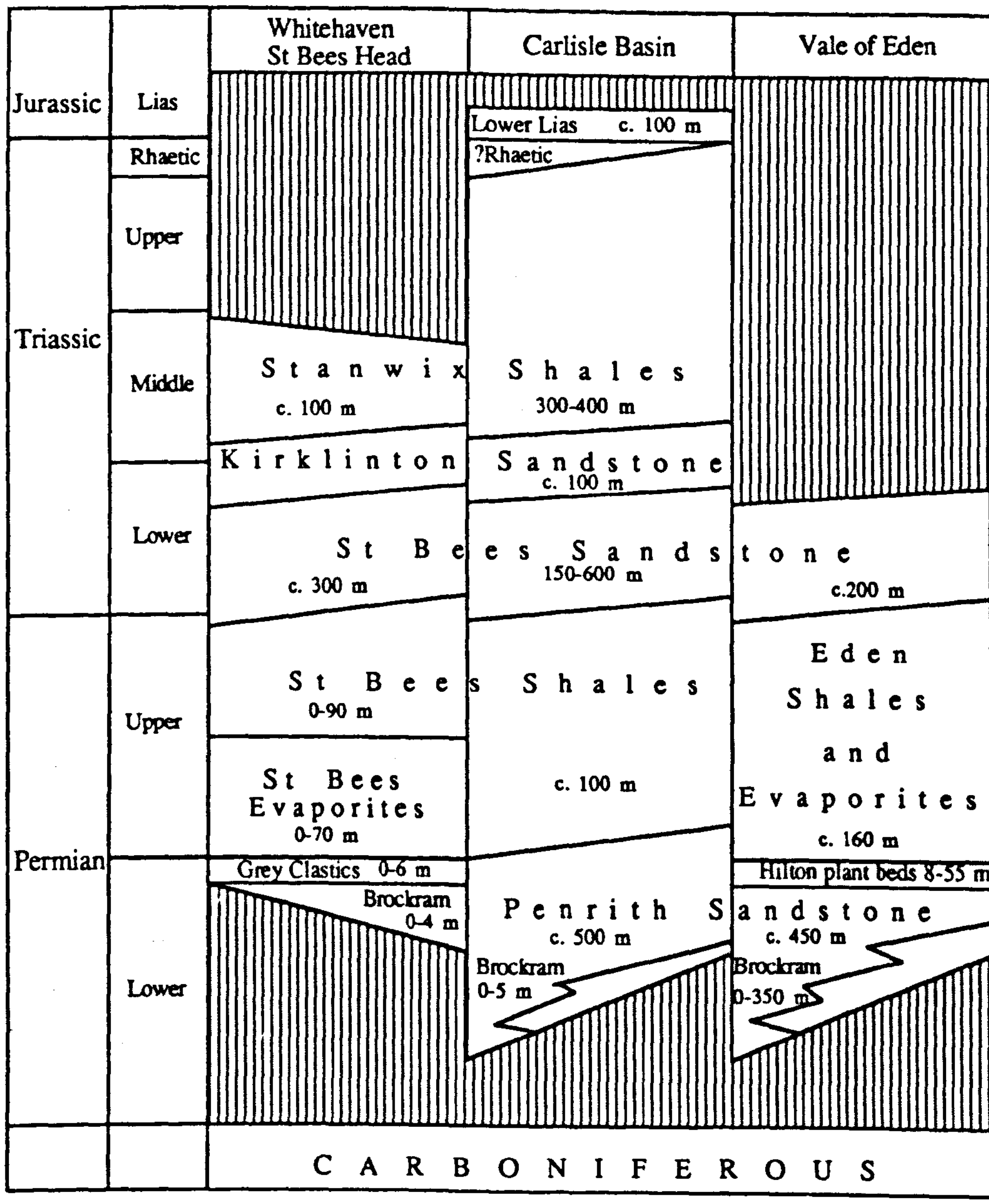


Figure 1.10 Permian and Triassic sequences in Whitehaven, Carlisle Basin and Vale of Eden (from Abbot 1987, Figure 5).

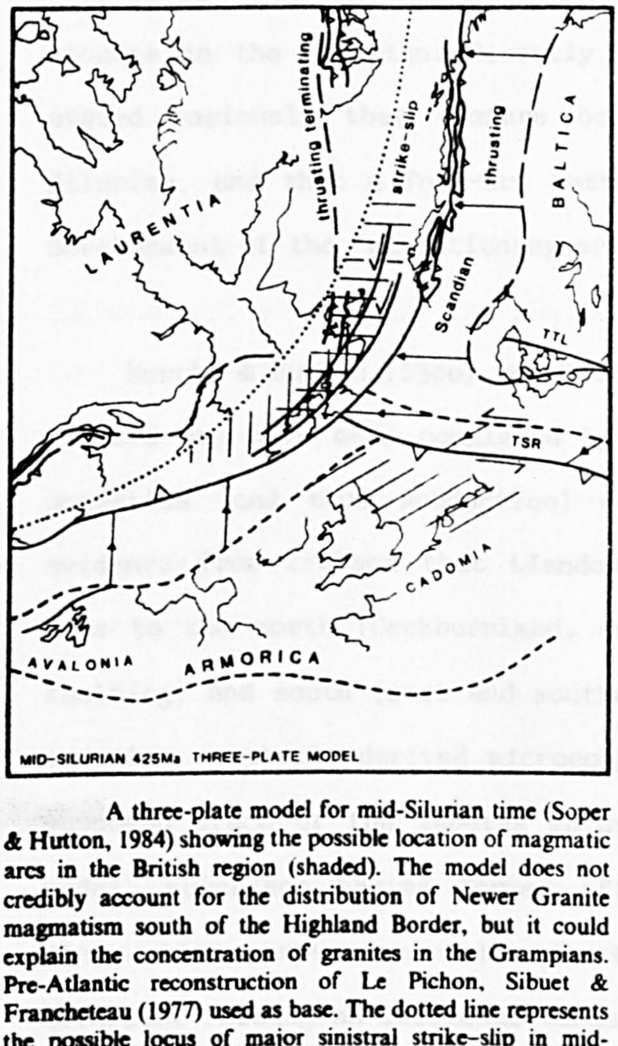
1.3 PLATE-TECTONIC SETTING: REVIEW OF GEOLOGICAL EVIDENCE

The Lower Palaeozoic inlier of the Lake District occupies a position just to the south of the Solway line, which on both faunal and geophysical evidence is believed to mark the trace of the Iapetus Suture (references cited below). The nature of the Iapetus convergence zone has been the subject of intense debate since the existence of an Ordovician 'proto-Atlantic' ocean was first proposed (Wilson 1966).

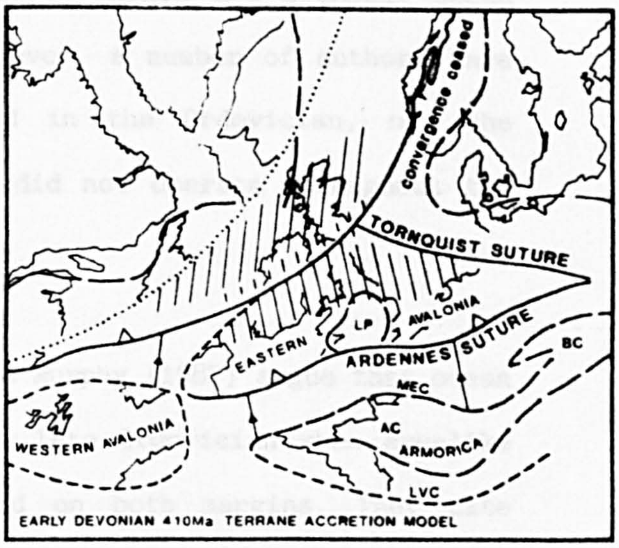
Early models of Caledonian plate-tectonics (e.g. Phillips et al. 1976) were developed in terms of a two-plate collision between Laurentia and 'Europe' which implied roughly E-W convergence in the northern part of the orogen (north-west Scotland, Greenland and Scandinavia) and NE-SW dextral transpression across the British and Irish sectors. Southward subduction beneath the Lake District was assumed to have ceased by the end of the pre-Ashgill volcanism represented by the Borrowdale Volcanic Group but northward subduction beneath the Southern Uplands continued into the Silurian and true continental collision was delayed until the end of the Silurian (Moseley 1978).

In recent years several lines of evidence have led to a modification of the original two-plate model. Soper & Hutton (1984) argued that the Caledonian orogeny involved three plates, not two; Baltica being separated from a third terrane (Cadomia) by the Tornquist's Sea. They cited three lines of evidence in support of this model. Firstly, that late Caledonian plate convergence in Britain was sinistrally, rather than dextrally transpressive, as indicated in particular by the way in which early Devonian cleavage in the slate belts on both sides of the Iapetus suture transect contemporaneous folds in a clockwise sense. Secondly, that evidence from the provinciality of Cambro-Ordovician shelf faunas (Cocks & Fortey 1982) indicated that there was wide separation in the Ordovician across the Tornquist's Sea between Baltica and a Gondwana-derived microcontinent of which southern Britain was a part. Thirdly, that the Caledonian deformation zone, which runs through north Germany and Poland, represents the Tornquist's Sea suture zone and is thus the third arm of a three plate collision, the other two arms represented by the Appalachian and North Atlantic Caledonides.

Soper (1986) developed the three-plate model a stage further in an analysis of the distribution and timing of the Caledonian 'Newer Granites' in Britain, which include the Lake District granites. He pointed out that the granites north of the Highland Border fault could be related to the westward subduction of Baltic lithosphere beneath the eastern edge of Laurentia or to northward subduction of Iapetus oceanic lithosphere beneath the Laurentian margin. Likewise, those south of the Iapetus suture could be related to the south-westwards subduction of Tornquist's Sea lithosphere beneath Cadomia. However, a simple three-plate model does not easily account for the granites of the Southern Uplands zone nor the NE-SW alignment of the Leinster, Lake District and Weardale granites. To explain these Soper (1986) envisaged a more complex series of terrane accretion events (Figure 1.11) in which continental fragments were detached from Gondwana in the early Palaeozoic and moved northwards, separated by small ocean basins, to be accreted onto Laurentia/Baltica during late Silurian to mid Devonian times. This model associates the granites of the Southern Uplands and northern England with northward subduction between the London platform and the Ardennes.



A three-plate model for mid-Silurian time (Soper & Hutton, 1984) showing the possible location of magmatic arcs in the British region (shaded). The model does not credibly account for the distribution of Newer Granite magmatism south of the Highland Border, but it could explain the concentration of granites in the Grampians. Pre-Atlantic reconstruction of Le Pichon, Sibuet & Francheteau (1977) used as base. The dotted line represents the possible locus of major sinistral strike-slip in mid-Palaeozoic time. TSR – Tornquist's Sea remnant; TTL – Teisseyre–Tornquist line.



A terrane accretion model developed from that shown in Figure 3, but for early Devonian time, after Laurentia–Baltica closure. The late Caledonian magmatism in the Highlands and slate belts are related to Iapetus and Ardennes subduction respectively. AC – Armorican craton; BC – Bohemian craton; MEC – Mid-European Caledonides; LP – London Platform; LVC – Ligurian–Vosgian cordillera.

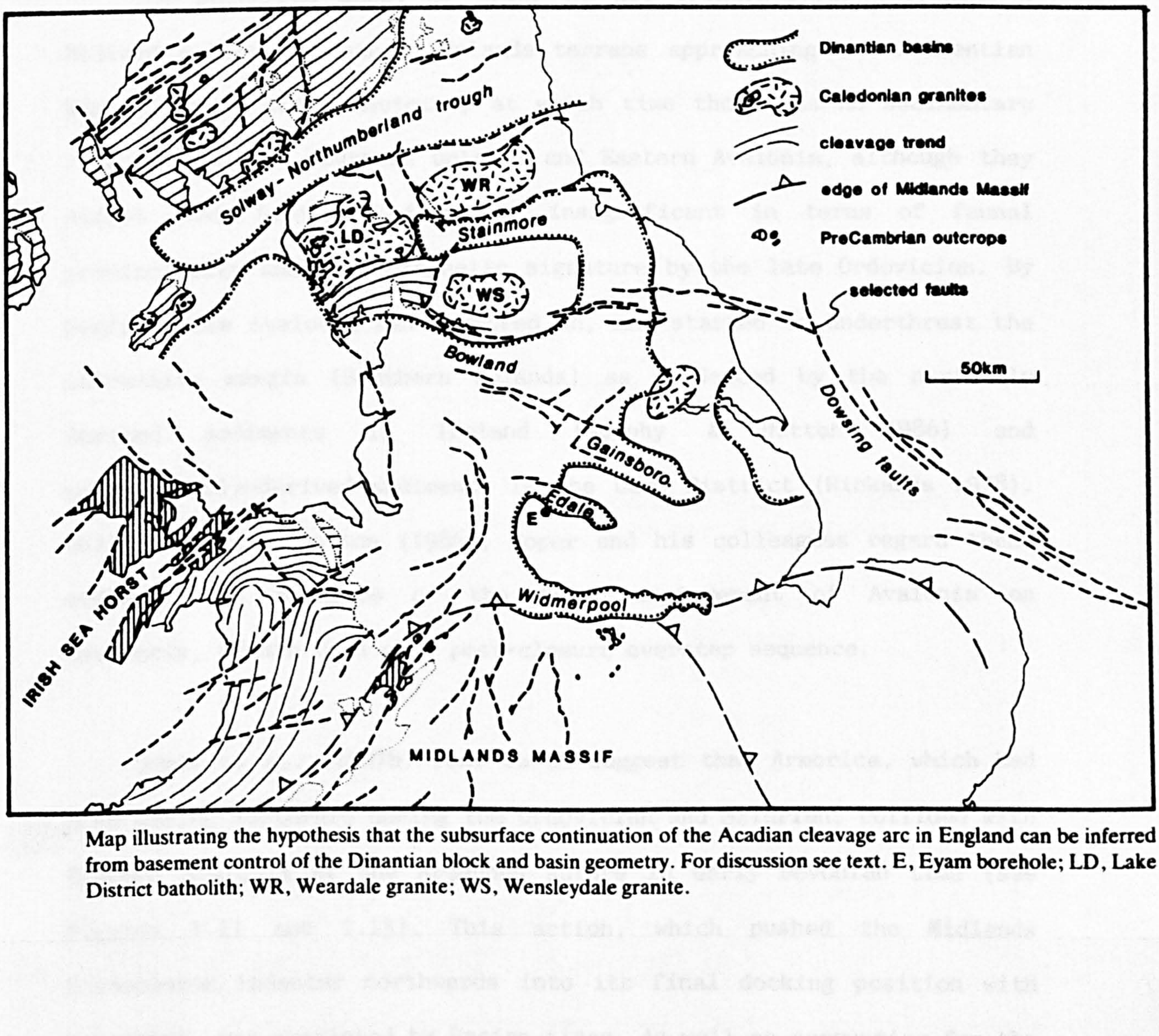
Figure 1.11 Terrane accretion model for Iapetus closure (from Soper 1986, Figures 3 and 4, including original captions).

At the same time that Soper was developing his three-plate model, controversy continued regarding the evolution of the Southern Uplands Caledonides, now juxtaposed across the Solway line immediately to the north of the Lake District. The original accretionary prism model (McKerrow et al. 1977, Leggett et al. 1979a,b and 1983) envisaged a simple fore-arc setting with northwestward subduction of Iapetus oceanic lithosphere beneath the Laurentian margin and eventual ocean closure in the Silurian. Recently, however, a number of authors have argued variously that closure occured in the Ordovician, not the Silurian, and that a fore-arc setting did not operate throughout the development of the 'accretionary prism'.

Murphy & Hutton (1986) and Hutton & Murphy (1987) argue that ocean closure may have been completed by the late Ordovician when arc-like magmatism (and thus subduction) ceased on both margins. They cite evidence from Ireland that Llandoverian sediments were derived from arcs to the north (Cockburnland, subsequently cut out by strike-slip faulting) and south (east and southeast Ireland and the Lake District) and that northerly-derived microconglomerates of Wenlock age span the supposed trace of the Iapetus suture. According to Murphy & Hutton's model, successor basins formed after closure and Cadomia continued slow, oblique movement northwards to dock finally at the end of the Silurian, forming an imbricate thrust stack in the central and southern belt of the Southern Uplands. Stone et al. (1986 and 1987) proposed a back-arc situation for the early (Llandeilo to mid-Llandovery) development of the Southern Uplands. According to this model, subduction ceased as oblique collision took place in the Llandovery. A south-east propagating thrust stack deformed the back-arc basin sequence and may have ramped over the eroded remains of the volcanic arc. The Wenlock and late Llandovery sequences were then deposited in a foreland basin formed ahead of the rising thrust stack. These and other papers relating to the Southern Uplands are reviewed by McKerrow (1987).

The theme of sinistral strike-slip in the end-Silurian to early Devonian period was discussed by Hutton (1987) who suggested that a clockwise-rotating Gondwanaland carried Laurentia into collision with Baltica and then broke free to create a major sinstral strike-slip zone. He envisaged a series of disorganized terranes originating to the southwest on the Laurentian and Gondwanaland margins prior to the Silurian. In this model the Lake District was seen (as in some earlier two-plate models, above) as part of an arc associated with southeastward subduction beneath Gondwanaland which climaxed in the mid-Ordovician. Hutton regards Iapetus as an Ordovician Ocean which closed before the Silurian and interprets the Southern Uplands and its Irish equivalents (his central zone) as an overstep assemblage which blankets the junction between Laurentian and Gondwanaland-derived terranes.

Some of the divergent views expressed above were discussed by Soper et al. (1987b) in an examination of evidence for late Caledonian transpression in North-west England. They stressed that late Caledonian structure to the south of the Solway line is not 'Caledonoid' (NE-SW) but arcuate, the arc marking a change from a NE-SW Appalachian trend to the SSE Tornquist trend. The arcuate structures appear to be moulded around the northern flank of the Midlands Massif (Figure 1.12) which they suggest acted as a 'rigid indenter' moving northwards into a embayment formed by the earlier suturing of Laurentia and Baltica. They



Map illustrating the hypothesis that the subsurface continuation of the Acadian cleavage arc in England can be inferred from basement control of the Dinantian block and basin geometry. For discussion see text. E, Eyam borehole; LD, Lake District batholith; WR, Weardale granite; WS, Wensleydale granite.

Figure 1.12 Cleavage in northern England (from Soper et al. 1987b, Figure 7, including original caption).

also cited evidence that the deformation of the cleavage arc was not end-Silurian but of early Devonian age and approximately synchronous with the Acadian orogeny of Canada.

The preferred model of Soper et al. (Figure 1.13) envisages a Midland Valley - Southern Uplands terrane approaching the Laurentian Margin during the Ordovician, at which time there was no sedimentary link between the Southern Uplands and Eastern Avalonia, although they accept that Iapetus had become insignificant in terms of faunal provinciality and palaeomagnetic signature by the late Ordovician. By Wenlock time Avalonia had impinged on, and started to underthrust the Laurentian margin (Southern Uplands) as evidenced by the northerly derived sediments in Ireland (Murphy & Hutton 1986) and northwesterly-derived sediments in the Lake District (Rickards 1978). Unlike Murphy & Hutton (1986), Soper and his colleagues regard these sediments as evidence of the first impingement of Avalonia on Laurentia, rather than as a post-closure overstep sequence.

Soper et al. (1987b) went on to suggest that Armorica, which had been moving northward during the Ordovician and Silurian, collided with Eastern Avalonia at the Ardennes suture in early Devonian time (see Figures 1.11 and 1.13). This action, which pushed the Midlands Microcraton indenter northwards into its final docking position with Laurentia, was completed by Emsian times. As well as accounting for the timing and arcuate trend of the late Caledonian structures in the southern British terrane, the indenter model also accounts for sinistral displacements in northern Britain (e.g. Soper & Hutton 1984, Hutton 1987) with major sinistral strike-slip taking place in the Silurian as Eastern Avalonia moved northwestwards along the Laurentian

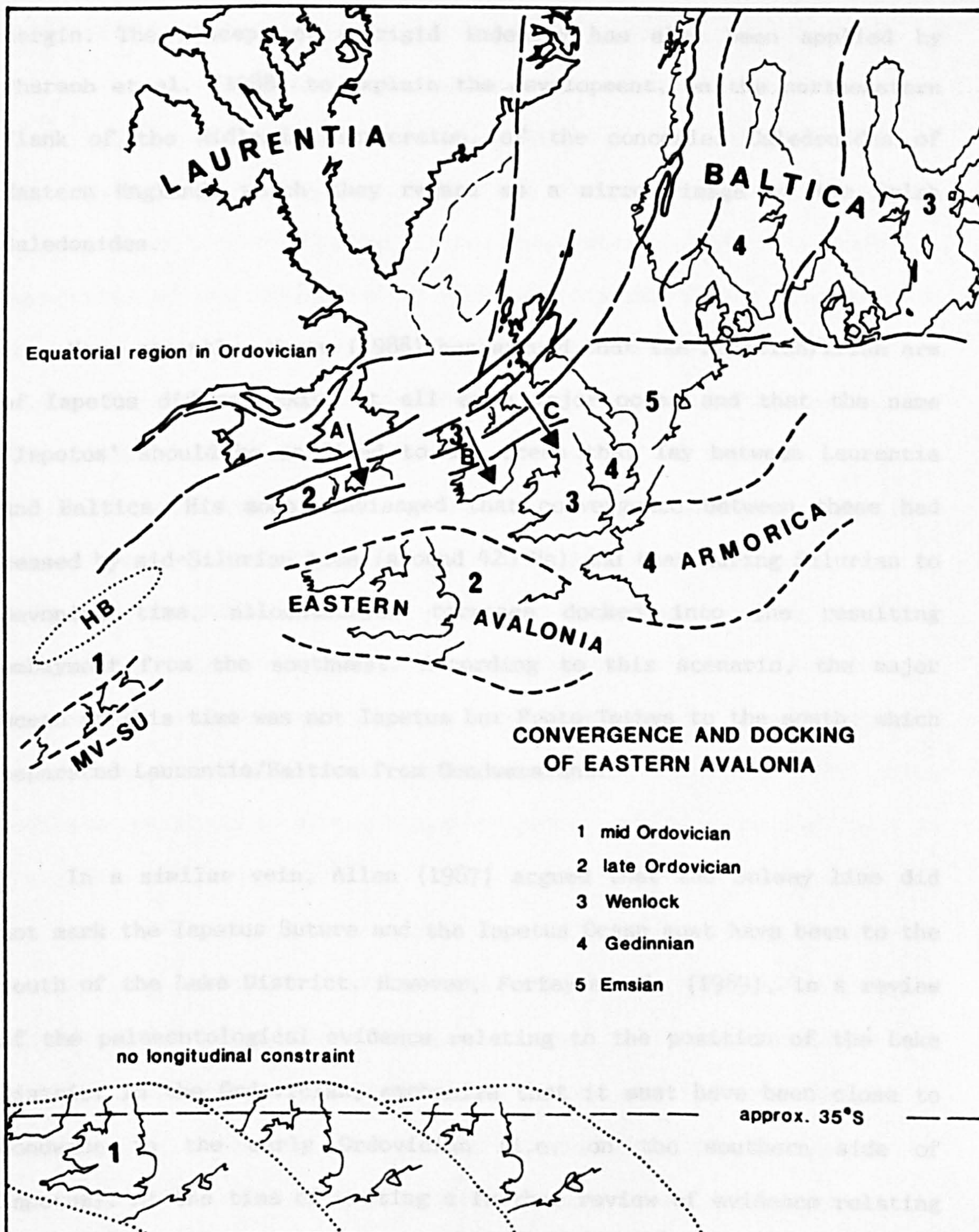


Fig. 9. A model for the convergence and docking of terranes in the British sector of the Caledonides. Successive positions of Eastern Avalonia are shown for (1) mid Ordovician (c.465 Ma), (2) late Ordovician (c.445 Ma), (3) Wenlock (420 Ma), (4) Gedinnian (410 Ma) and (5) Emsian (395 Ma). Selected positions of the Highland Border terrane (HB), Midland Valley – Southern Uplands terrane (MV-SU), Armorica and Baltica are also shown. The principal constraints are: 1-3 palaeomagnetic evidence (Piper 1978 and pers. comm.); 2-3 sedimentary provenance links (A, Elders 1986; B, Murphy & Hutton 1986; C, Lake District turbidites, see text); 4-5 final docking trajectory for Eastern Avalonia from this paper.

Figure 1.13 Terrane model for Iapetus closure (from Soper et al. 1987b, figure 9, including original caption).

margin. The concept of a rigid indenter has also been applied by Pharaoh et al. (1988) to explain the development, on the northeastern flank of the Midlands microcraton, of the concealed Caledonides of Eastern England, which they regard as a mirror image of the Welsh Caledonides.

More recently, Mason (1988) has argued that the Scottish/Irish arm of Iapetus did not exist at all as a major ocean and that the name 'Iapetus' should be confined to the ocean that lay between Laurentia and Baltica. His model envisaged that convergence between these had ceased by mid-Silurian time (around 420 Ma) and that during Silurian to Devonian time, allochthonous terranes docked into the resulting embayment from the southwest. According to this scenario, the major ocean at this time was not Iapetus but Proto-Tethys to the south, which separated Laurentia/Baltica from Gondwanaland.

In a similar vein, Allen (1987) argued that the Solway line did not mark the Iapetus Suture and the Iapetus Ocean must have been to the south of the Lake District. However, Fortey et al. (1989), in a review of the palaeontological evidence relating to the position of the Lake District in the Ordovician, emphasize that it must have been close to Gondwana in the early Ordovician (i.e. on the southern side of Iapetus). At the time of writing a further review of evidence relating to the nature of the Iapetus Suture in the British Isles has been published by McKerrow & Soper (1989) which reinforces the view that Iapetus existed as a major ocean to the north of the Lake District.

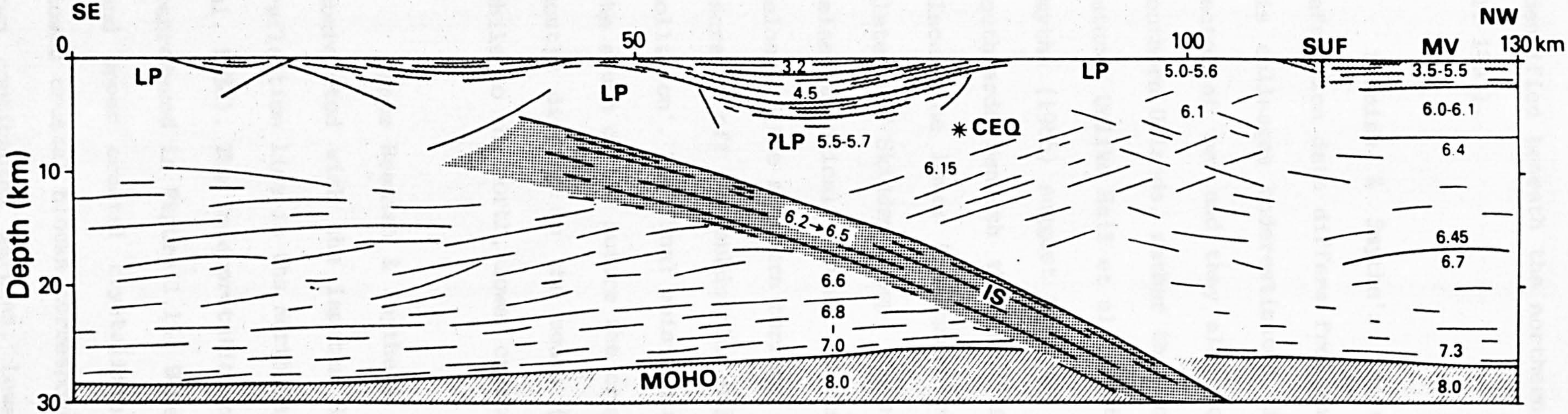
1.4 DEEP STRUCTURE: REVIEW OF GEOPHYSICAL EVIDENCE

A common feature of most of the plate-tectonic reconstructions discussed above is that crust belonging to the southern Britain (Eastern Avalonia in some models) was thrust beneath the Southern Uplands along a north-dipping suture. Geophysical evidence is generally supportive of the concept of a northward-dipping suture zone beneath the Solway line, separating contrasting crustal blocks to the north and south. The most important evidence comes from the deep reflection seismic data collected by the BIRPS group across the supposed suture in the Irish Sea (line WINCH-2, Brewer et al. 1983)) and North Sea (line NEC, Klemperer & Matthews 1987). Both show north-dipping zones of reflections although there are important differences in the character of the upper and lower crust between the two sections (see below). Supporting evidence is provided by a series of magnetotelluric measurements in the Northumberland Trough (Beamish & Smythe 1986) which indicate the presence of a northward-dipping highly conductive layer in the middle and lower crust.

Seismic refraction surveys have provided information on the velocity/depth structure of the crust but in certain respects the results from lines across the Iapetus strike have differed from those along strike. The major cross-strike experiment (LISPB, Bamford et al. 1978) showed a discontinuity in the mid and lower crust beneath the Southern Uplands blanketed by a thick (around 15km) layer of Lower Palaeozoic sedimentary rocks (Vp = 5.8 - 6.0 km/sec) extending into northern England. However, Hall et al. (1983) provided evidence from an along-strike line for high velocity basement (6.0 to 6.3 km/sec) at shallow depth (1 km) beneath the northern part of the Southern Uplands which they interpreted as continental crystalline basement capped by the remnants of the accretionary prism.

Bott et al. (1985) also found evidence for high velocity (6.15 km/sec) basement at relatively shallow depth (4 km) beneath the Northumberland Trough and Irish Sea, from an along-strike refraction line. This was interpreted as 'southern' continental crystalline basement beneath a thin Lower Palaeozoic sequence. The crystalline layer has a well-defined base at a depth of about 16 km beneath the North Sea and Northumberland Trough but its base is undetermined beneath the Irish Sea. Bott et al. (1985) also noted a difference in the character of the Moho between the North Sea (relatively sharp) and the Irish Sea (gradational) and tentatively suggested that this might indicate the juxtaposition of different crustal types along strike to the south of the suture.

Beamish & Smythe (1986) synthesized the seismic and geoelectric evidence available by the end of 1985 into a generalized model which is reproduced in Figure 1.14. As well as the WINCH data and the refraction data mentioned above, the model incorporates commercial reflection data from lines between the Lake District and the Isle of Man. These authors correlate the highly conducting layer delineated by the magnetotelluric observations (in the Northumberland Trough) with the upper surface of the wedge of lower crustal reflectors interpreted as the trace of the Iapetus suture (in the Irish Sea). The commercial lines show both northerly and southerly dipping reflectors beneath an accoustically blank zone correlated with the Lower Palaeozoic rocks of the Southern Uplands and northern England. The southerly dipping reflectors are extrapolated northwards and correlated with the 6.1 km/s basement



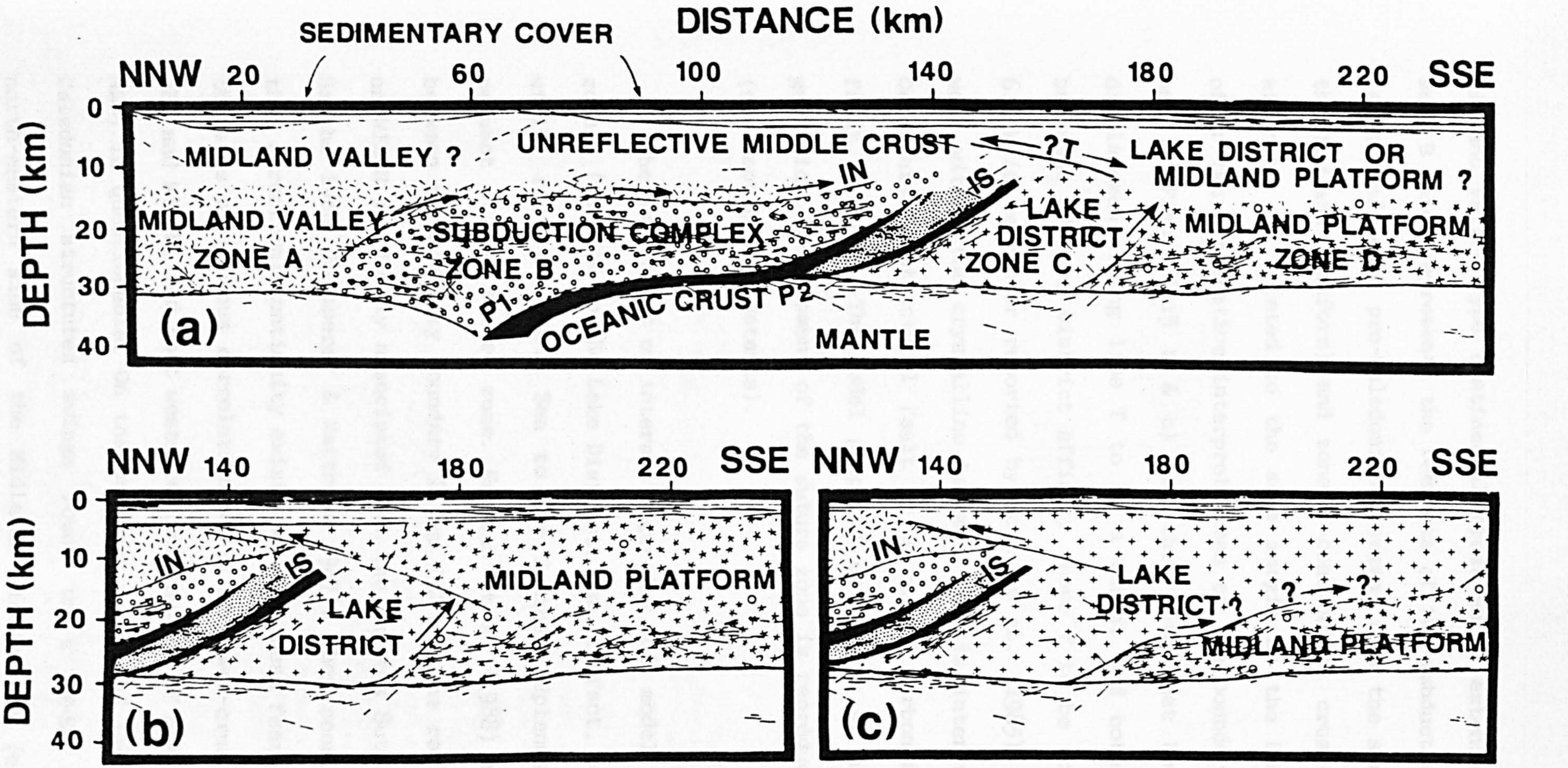
Speculative geological cross-section through the region of the Iapetus suture (IS) where the experiments shown in Fig. 1 are clustered, assuming a large degree of 2-dimensional continuity along 200 km of strike. It is loosely based on deep seismic reflection structure, with the addition of P-wave velocities (km s^{-1}) from the various refraction experiments—see text for discussion. Bold stippled area represents the highly conducting layer (HCL), which has resistivity of the order of 1-20 ohm m. Light stipple, Upper Palaeozoic sediments. LP, Lower Palaeozoic; CEQ, schematic hypocentre of the Carlisle earthquake (see text); SUF, Southern Uplands fault; MV, Midland Valley.

Figure 1.14 Speculative geological cross-section through the Iapetus suture from the WINCH line and deep conductivity data (from Beamish and Smythe 1986, Figure 7, including original caption).

identified beneath the northern part of the Southern Uplands (Hall et al. 1983).

Beamish & Smythe's interpretation of Bott et al.'s (1985) refraction data differs from the original. They contend that Bott and his colleages underestimated the depth to continental basement by a factor of two and they also equate this crust with that beneath the Southern Uplands, rather than with crust from the southern side of the suture. Unlike Hall et al. (1984) and Needham & Knipe (1986), Beamish & Smythe (1986) suggest that the 'geophysically defined suture' extends southwards beneath the Lake District and Isle of Man which in turn places the Lower Palaeozoic rocks of these regions (e.g. the Manx Slates and Skiddaw Group) above and to the north of the suture. As, on palaeontological grounds (Cocks & Fortey 1982), these rocks clearly belong to the southern terrane, Beamish & Smythe suggest that they were 'scraped off the subducting passive margin during the final stages of collision'. The final point to note regarding the WINCH data is that to the south of the suture the crust shows good lower crustal reflections, mostly dipping to the south (Figure 1.14), and a well imaged Moho, while to the north, lower crustal reflectors are rare.

Since Beamish & Smythe's synthesis, northerly dipping reflectors correlated with the Iapetus Suture have been identified on the NEC reflection line in the North Sea (Klemperer & Matthews 1987, Freeman et al. 1988). The interpretation of NEC given by Freeman et al. (1988) is reproduced in Figure 1.15. Beneath the thin sedimentary cover sequence and upper crustal crystalline rocks, they recognized four adjacent lower crustal blocks corresponding to distinct terrane types from the two continental margins. Lower crustal zone A represents 'normal'

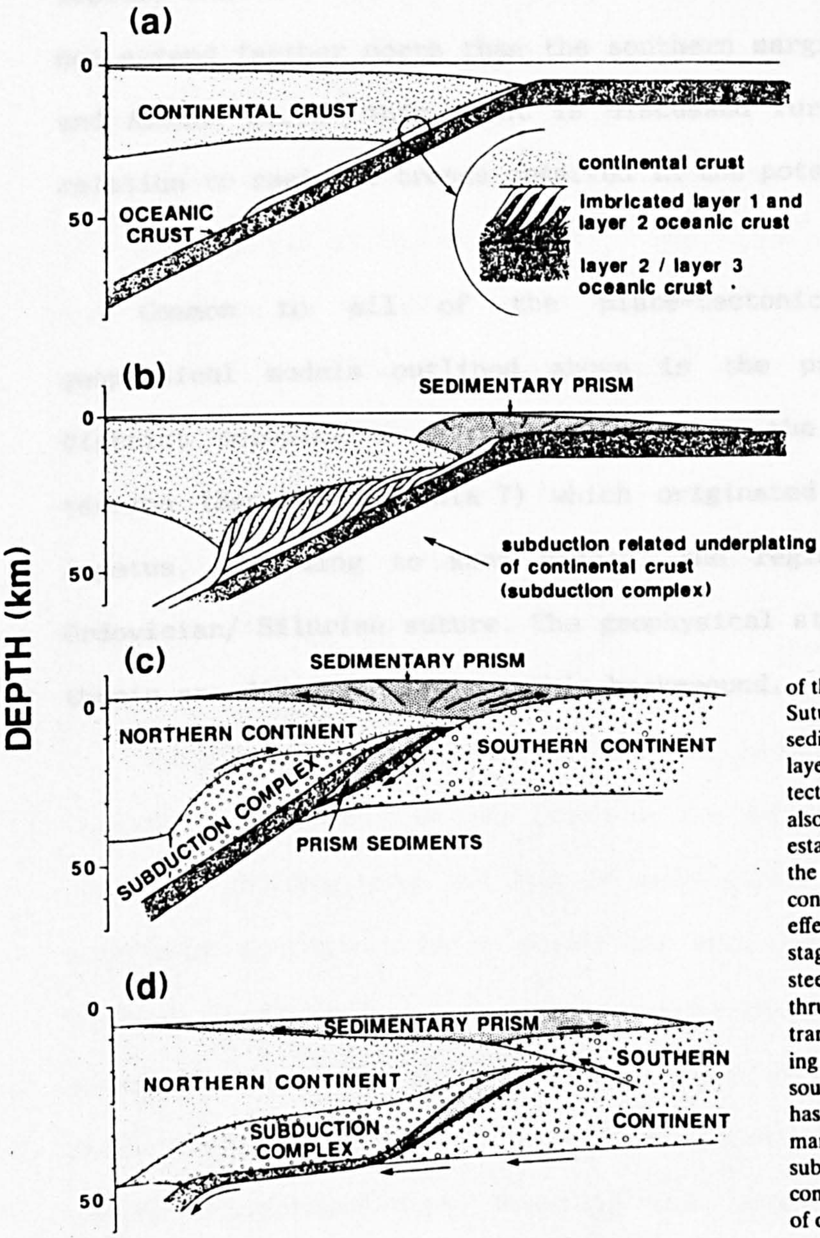


(**a**) Geological interpretation of the migrated depth section; lower crust *only*. Alternative explanations of the southern half of the NEC-line based on (**b**) a steep contact between zones C and D which extends to the top of basement, and (**c**) a shallow boundary between rocks of Lake District affinity and the Midland Platform basement.

Figure 1.15 Geological interpretation of the NEC line (from Freeman et al. 1988, Figure 6, including original caption).

Midland Valley type continental crust which extends southwards above zone B which represents the remnants of the subduction complex. Zone D is assumed to be pre-Caledonian basement from the southern plate (i.e. the Midland Platform) and zone C continental crust, possibly of arc affinity and related to the same margin as the Lake District. They offer two alternative interpretations of the boundary between zones C and D (Figure 1.15 b & c) but they note that both require a net displacement along line T to be a thrust and both have crystalline basement of Lake District affinity above T to be consistent with the 6.1 km/s refractor reported by Bott et al. (1985). Reflector T lies well within the crystalline basement and is interpreted as either a Caledonian contractural fault or Devonian/ Carboniferous extensional fault, or both. The model proposed by Freeman et al. (1988) for the geological development of the suture zone is reproduced in Figure 1.16 (see caption for details).

The main point of interest regarding this model is whether crustal zone C (related to the Lake District) can, in fact, be correlated along strike from the North Sea to the Southern Uplands - Lake District segment of the suture zone. Freeman et al (1988) noted similarities between reflectivity boundary IN on NEC and the reflectivity boundary on WINCH previously associated with the Iapetus Suture (e.g. Beamish & Smythe 1986, Klemperer & Matthews 1987). They considered it possible that structural continuity exists between these features but noted that there is no obvious correlation of IS or lower-crustal zone B between NEC and WINCH, and that westward continuation of other structures (from NEC) is questionable. On the southern margin of Iapetus the strike of Caledonian structures swings round to a NW-SE direction on the north-eastern side of the Midlands Microcraton (e.g. Soper et al.



Schematic model for the geological development of the deep structure of northern England and the Iapetus Suture zone. (**a**) Early subduction history pre-sedimentary prism development. Imbrication of oceanic layer 1 and layer 2 sediments and volcanics produces a tectonically thickened skin to the subducting slab (see also Clowes *et al.* 1987). (**b**) Sedimentary prism well established. Imbrication of the sediment/volcanic skin of the slab with slices of rock flaked off from the over-riding continental crust. Stacking of crude duplex structures effectively underplates the continental crust. (**c**) Initial stages of continental collision and continental subduction, steepening of slab and subduction complex, under-thrusting of oceanic crust with prism sediments which are transported downwards. Main period of crustal thickening prior to decoupling of crust and mantle of the southern continent. (**d**) Subduction of continental crust has now ceased but continued northerly motion of the mantle lithosphere smears oceanic crust and the subduction complex along the base of the northern continental crust. Contraction finally stops leaving a tail of oceanic crust in the uppermost mantle.

Figure 1.16 Schematic model for the development of the Iapetus suture zone (from Freeman et al. 1988, Figure 8, including original caption).

1987b, see discussion in previous section). Freeman et al. recognized this problem and postulated that the seismically transparent zone above zones C and D could represent deformed early Palaeozoic sediments above the deep northeast margin of the microcraton. However, their model implies that the NW-SE structures associated with Tornquist closure do not extend farther north than the southern margin of the Lake District and Alston Block. This point is discussed further in Section 6.7 in relation to regional trends observed in the potential field data.

Common to all of the plate-tectonic reconstructions and geophysical models outlined above is the proposal that the Lake District occupies a crucial position on the northern margin of a terrane (Eastern Avalonia ?) which originated on the south side of Iapetus. According to some models, the region now lies above the Ordovician/ Silurian suture. The geophysical studies presented in this thesis are discussed against this background.

CHAPTER 2

GRAVITY AND AEROMAGNETIC SURVEYS

2.1 REGIONAL AND DETAILED GRAVITY SURVEYS

A total of 2213 new gravity observations was recorded in the Lake District during 1980 and 1981 as part of the national coverage. Helicopter transport was used to gain access to remote areas in order to achieve an even coverage of observations. The average distribution of observations is approximately 1 per 2 km^2 which is close to the coverage usually achieved in lowland areas. The new survey supersedes the widely distributed (1 per 5 km^2) observations reported by Bott (1974). The survey was carried out by the author and his colleagues in the Applied Geophysics Unit of the Institute of Geological Sciences (now the Regional Geophysics Research Group of BGS). The author acted as party chief for the helicopter-born survey of the high ground.

Normal BGS survey practice was followed; gravity base stations were established in the area prior to the survey and base readings were taken at the begining and end of each survey loop. The observations were made mainly at bench marks and spot heights using LaCoste and Romberg gravity meters. In certain remote areas, where spot heights are particularly widely spaced, observations were also taken at points whose elevations were determined from contours shown on the OS 1:10,000 series topographic maps. Provided that these positions are carfully chosen (i.e. on flat ground at identifiable features such as fence junctions), the elevation of such points is usually accurate to within about 1 m. This is considered acceptable in a mountainous region where terrain corrections often reach several mGal.

Data reduction was carried out according to normal BGS practice (Turnbull 1978), in this case by vacation students working under the supervision of the author. Inner zone terrain corrections (to Hammer Zone G) were estimated from OS 1:10,000 scale topographic maps using standard Hammer Charts. Outer zone terrain corrections (to a radius of 48.63 km) were computed automatically from a a databank of average elevations over 1 km squares (unpublished BGS software, G. Turnbull). Bouguer anomalies were calculated against the Inernational Gravity Formula 1967 and referred to the National Gravity Reference Net 1973. The data were incorporated into the National Gravity Data Bank (NGDB) held by BGS and are not listed in this thesis.

By default, the data processing software assumes a density of 2.70 Mg/m^3 for calculating Bouguer corrections and it is the Bouguer anomaly values so calculated which are stored in the NGDB. However, the software for extracting the data from the NGDB (unpublished BGS software, G. Turnbull & I.F. Smith) allows for the recalculation of Bouguer anomalies at any user-defined density (see Chapters 6 and 7).

Since the Lake District regional survey, gravity coverage in the surrounding areas has been completed by BGS as part of the national survey and the data lodged in the National Gravity Data Bank. Sea bottom data from the Irish Sea, to the west of the Lake District, were published by Bott (1964) and are also held in the data bank.

During 1982-4 the original regional gravity data were supplemented in the western Lake District by 501 additional (in-fill) regional observations and 579 closely-spaced observations along 12 traverses as part of the Lake District multidisciplinary project. The objective of these was to improve the resolution of the anomalies over the Eskdale and Ennerdale granites and in the Crummock Water area. The data were collected by the author and field teams under the supervision of the author (the author is particularly indebted to A.S.D. Walker (BGS) who collected over 50% of the data with the help of vacation students). Survey procedures for the in-fill regional observations were as described above for the original regional survey. The detailed traverses were carried out along roads and tracks. Station elevations were determined to an accuracy of within 0.1 m by levelling between benchmarks using a tachiometric theodolite. Inner zone terrain corrections for the new observations were computed from a grid of average elevations over 250m squares derived OS 1:10,000 topographic maps (BGS software, G. Turnbull). Outer zone corrections (to a radius of 48.63 km) were computed as for the regional observations. The new data were also incorporated into the NGDB and are not listed here.

Traverse locations and regional station positions (original and supplementary surveys) for the western Lake District are shown on Figure 2.1 and the new Bouguer anomaly map of the western and central Lake District, based on the combined dataset, is shown in Figure 2.2. A contour map of the entire Lake District region, based on data from all sources is shown on Figure 2.3 (station locations are shown in Figure 2.4). Bouguer anomaly values for these maps were calculated assuming a density of 2.75 Mg/m^3 which is around the average for the Borrowdale Volcanic Group and considered to be a reasonable compromise given the range of density values in the Lake District (see Chapter 5). A Bouguer anomaly map of the wider region (northern England and southern Scotland), which incorporates all the data available to the

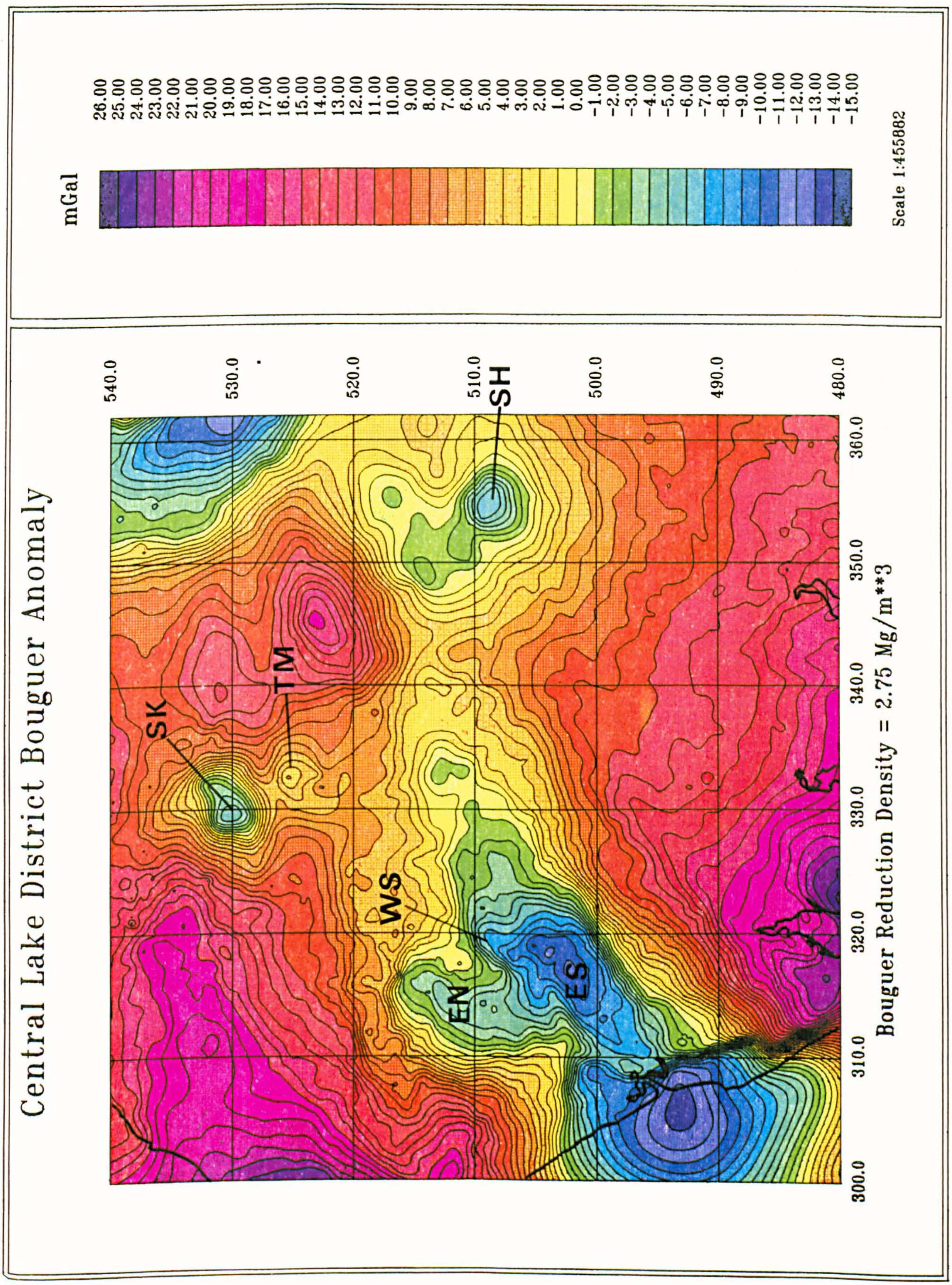


Figure 2.2 New Bouguer anomaly map of the central Lake District based on the combined dataset. Codes indicate anomalies as follows: EN = Ennerdale Granophyre, ES = Eskdale Granite, HW = Haweswater anomaly, SH = Shap Granite, SK = Skiddaw Granite, TM = Threlkeld Microgranite, WS = Wasdale Granite

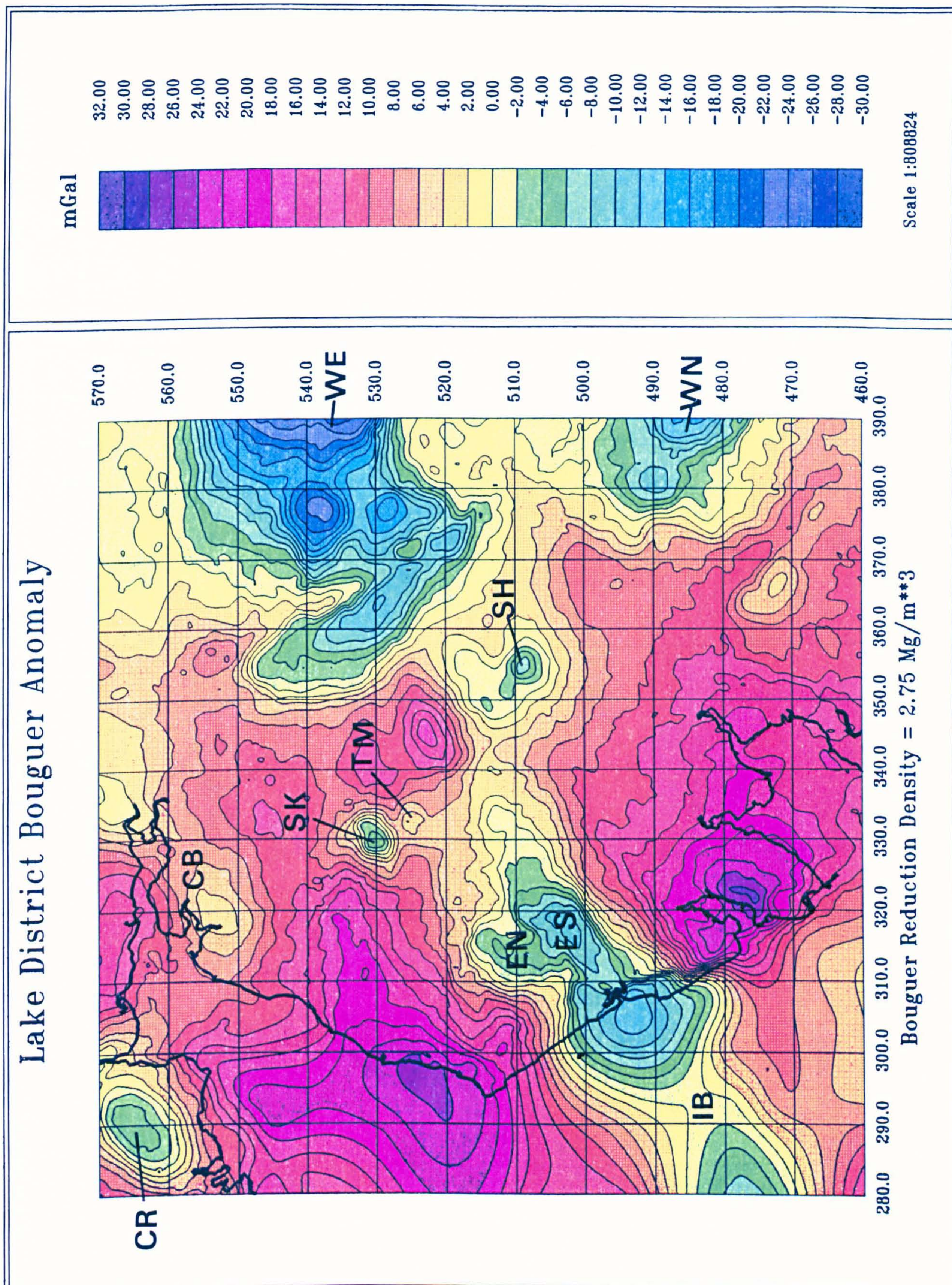


Figure 2.3 Bouguer anomaly map of the Lake District region based on data from regional and detailed surveys. Codes indicate anomalies as follows: EN = Ennerdale Granophyre, ES = Eskdale Granite, SH = Shap Granite, SK = Skiddaw Granite, TM = Threlkeld Microgranite, WE = Weardale Granite, WN = Wensleydale Granite, CR = Criffel Granodiorite, VE = Vale of Eden, CB = Carlisle Basin, IB = Irish Sea Basin.

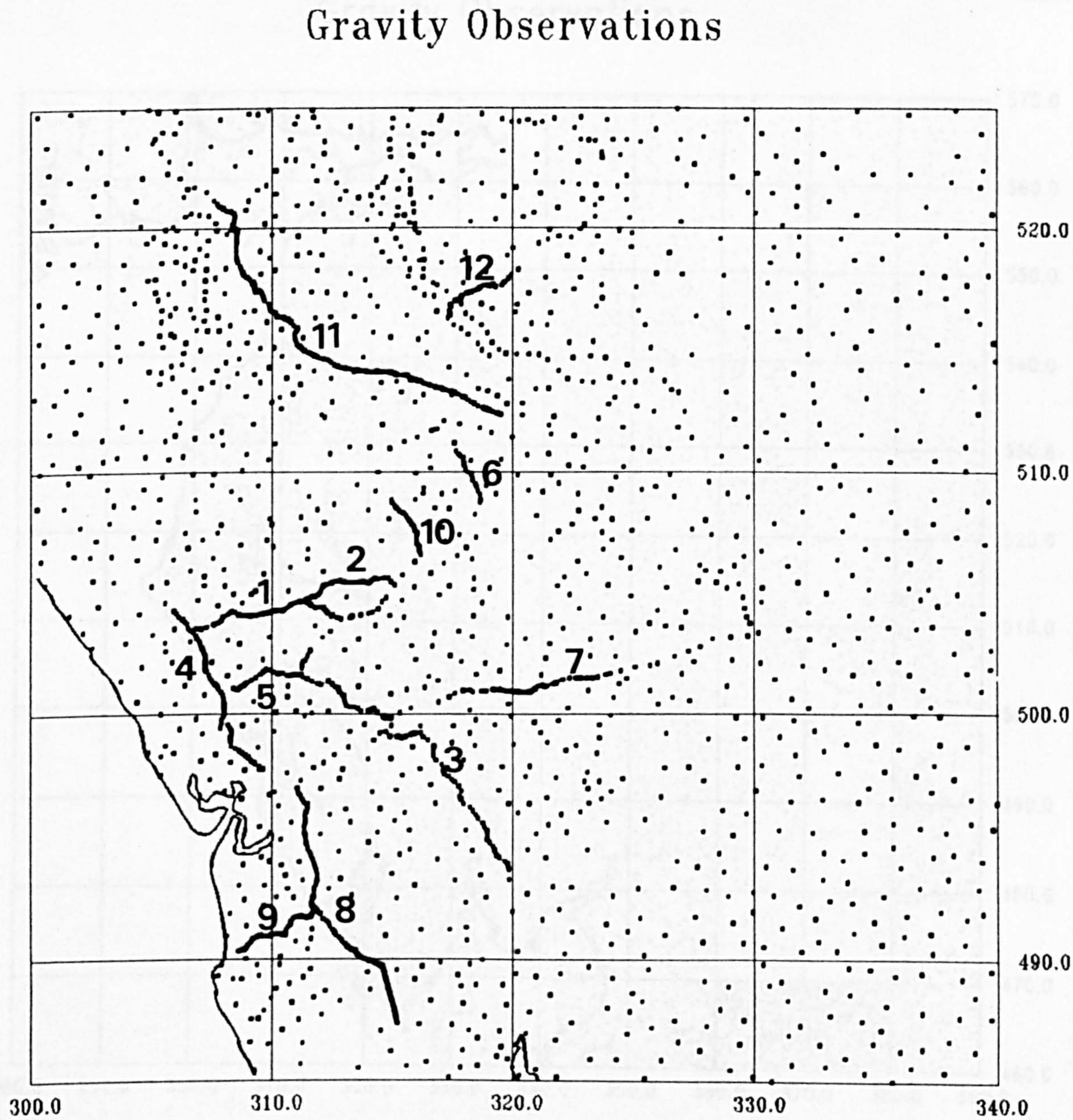


Figure 2.1 Gravity observations in the western Lake District (regional stations and in-fill observations). The numbers refer to the detailed traverses (see text).

Gravity Observations

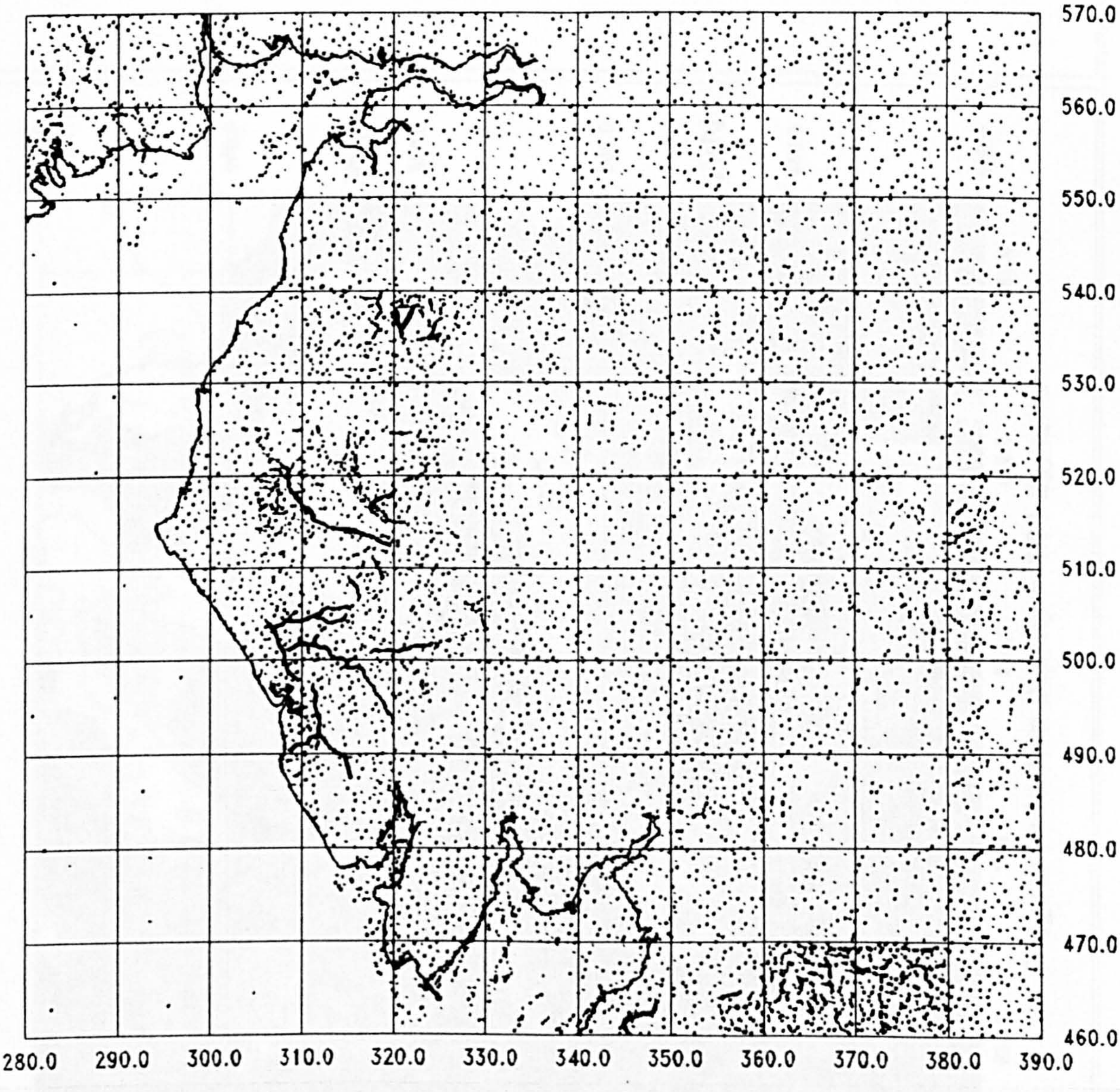


Figure 2.4 Location of regional and detailed gravity observations in the Lake District region (used to generate the map shown in Figure 2.3).

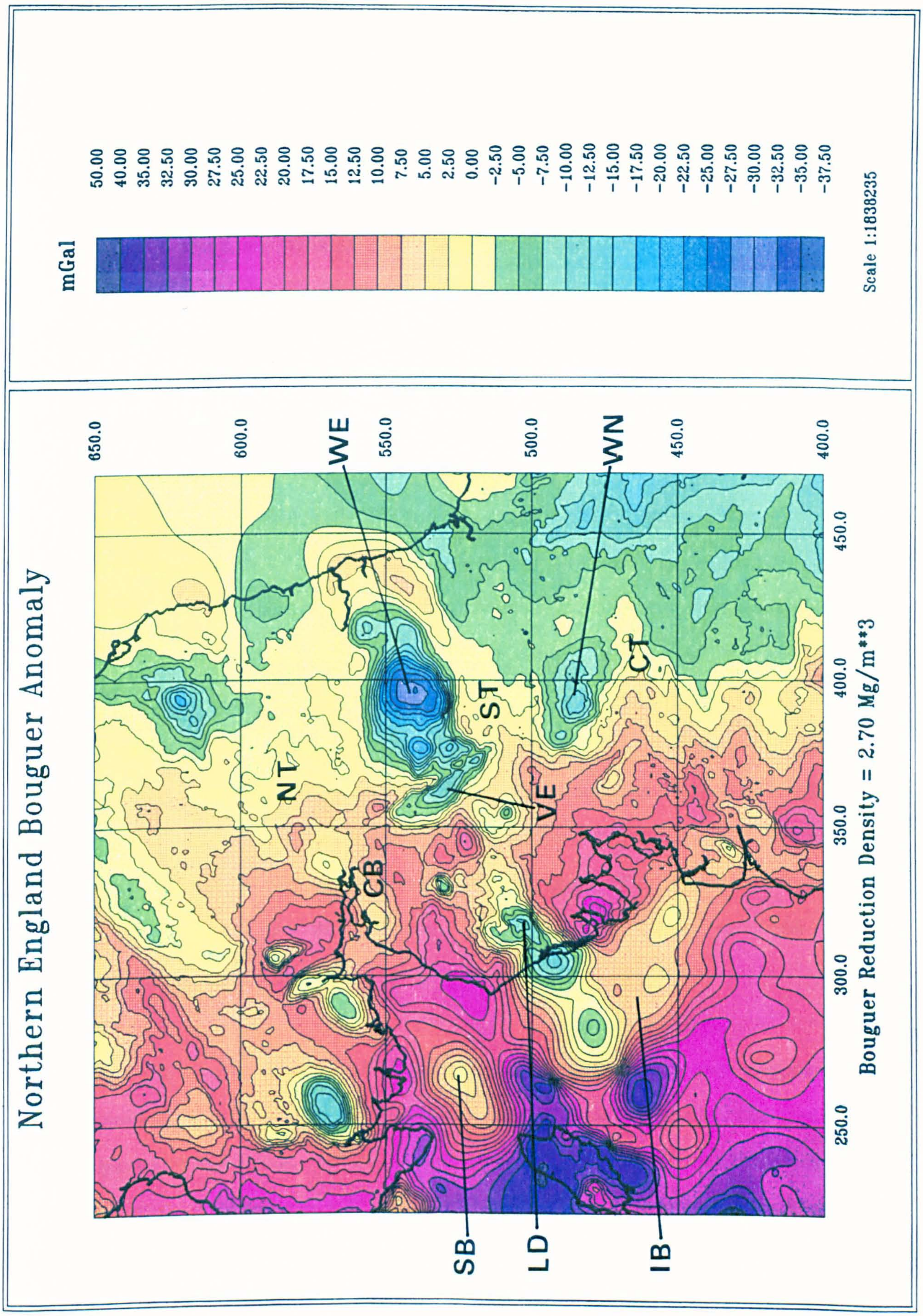


Figure 2.5 Bouguer anomaly map of northern England. Codes indicate anomalies as follows: CB = Carlisle Basin, CT = Craven Trough, IB = Irish Sea Basin, LD = Lake District Batholith, NT = Northumberland Trough, SB = Solway Basin, ST = Stainmore Trough, VE = Vale of Eden, WE = Weardale Granite, WN = Wensleydale Granite.

end of 1988, is shown in Figure 2.5. The map is based on the default Bouguer reduction density of 2.70 Mg/m^3.

2.2 THE MAIN FEATURES OF THE BOUGUER ANOMALY MAPS

Figure 2.5 clearly reflects the ENE trending Caledonian influence within the basement and the 'block and basin' structure of northern England. The blocks (e.g. Alston, Askrigg and the Lake District) are characterized by distinctive gravity lows due to the underlying low density granites (e.g. Weardale, Wensleydale and Lake District batholiths respectively). In contrast the Carboniferous basins (Northumberland, Stainmore and Craven) appear as relative gravity highs. However, this occurs only because the negative anomalies due to the granites have a greater magnitude than those due to the sedimentary sequences within the troughs - if the effects of the granites were to be removed, the Lower Carboniferous troughs would appear as relative gravity lows. Superimposed on these ENE-trending Caledonian features are the anomalies due to the later Permo-Triassic basins which trend mainly NNW. The Solway, Vale of Eden, and Irish Sea basins are all characterized by distinctive gravity lows due to the thick accumulations of low density sediments.

All of these individual anomalies are, in turn, superimposed on a general increase in the Bouguer anomaly level towards the Irish Sea regional high (e.g. 44 mGal over the Isle of Man), which is partially masked by the effects of the thick Permo-Triassic sequence in the Irish Sea Basin (Bott 1964, Bott & Young 1971) and by the western end of the granite batholith. Bott (1964) interpreted the Irish Sea high as being caused by either thinner or denser crust beneath the Irish Sea in relation to adjacent areas.

In the Lake District region itself (Figure 2.2 and 2.3) the Shap, Skiddaw, Eskdale and Ennerdale granites show up clearly as gravity lows. They are connected by a less distinct belt of generally low gravity over the central and northern parts of the Lake District. The gravity field is resolved in considerably more detail than on the previous regional map (Bott 1974). In particular the anomaly in the Skiddaw area has been resolved into separate lows, one associated with the main granite and the other with the Threlkeld Microgranite to the south. A distinct gravity gradient is apparent between the Eskdale Granite and the Ennerdale Granophyre, and the main Eskdale anomaly is seen clearly to include the Wasdale Granite. The belt of low gravity linking the outcrops appears to be associated more with the Eskdale/Ennerdale intrusions than with the Shap and Skiddaw granites where the anomalies are suggestive of being distinct and separate features superimposed on the broader gravity low. The Shap anomaly extends north-westwards to encompass the Haweswater Igneous Complex and is bounded on the northwest side by a gravity high centred over the Ullswater inlier of the Eycott Group.

The thick succession of Silurian sedimentary rocks in the southern part of the Lake District (the Windermere Group) has the effect of lowering the level of Bouguer anomaly in that area. The effect is significant but not immediately obvious. It is best illustrated by the abrupt decrease in the steepness of the gravity gradients associated with the southern side of the granite batholith. The Carboniferous, and particularly the Permo-Triassic basins around the Lake District cause distinctive negative gravity anomalies which interfere and overlap with those due to the granites and Silurian sediments. The thick Permo-Triassic successions on the eastern edge of the Irish Sea Basin and in the Vale of Eden, in particular, give rise to large negative anomalies and steep gradients.

2.3 AEROMAGNETIC DATA AND MAIN FEATURES OF THE AEROMAGNETIC MAP

The aeromagnetic survey of the Lake District was carried out by Canadian Aero Service Ltd in 1958 and 1959. In the southern part of the Lake District the survey was carried out along E-W flight lines at 2 km spacing with N-S tie lines at 10 km spacing; in the north of the area flight lines were orientated N-S and tie lines E-W (Figure 2.6). Mean terrain clearance was 305m. The data were recorded originally onto paper records. Contour maps were produced by plotting diurnally corrected total field values at 10 nT intervals, and all high and low points, onto 1:50K scale base maps and contouring by hand.

Within the past three years the Lake District aeromagnetic data have been digitized at BGS as part of a project to make the national dataset available in machine readable form. This was achieved by digitizing the diurnally corrected values (i.e. the high, low and 10 nT control points) along each flight line from the original base maps (see Figure 2.6). A contour map of the Lake District area, generated from the digitized data is shown in Figure 2.7.

The most prominent magnetic feature in the Lake District is the arcuate anomaly associated with the outcrop of Eycott Volcanic Group on the northern margin of the Lower Palaeozoic inlier. Distinctive anomalies are also associated with the Shap Granite and its aureole (Locke & Brown 1978) and the Ennerdale Granophyre, the latter being due to the highly magnetic microdiorite sheets within the intrusion (see Section 5.4.3). Elsewhere the Lower Palaeozoic rocks of the Lake

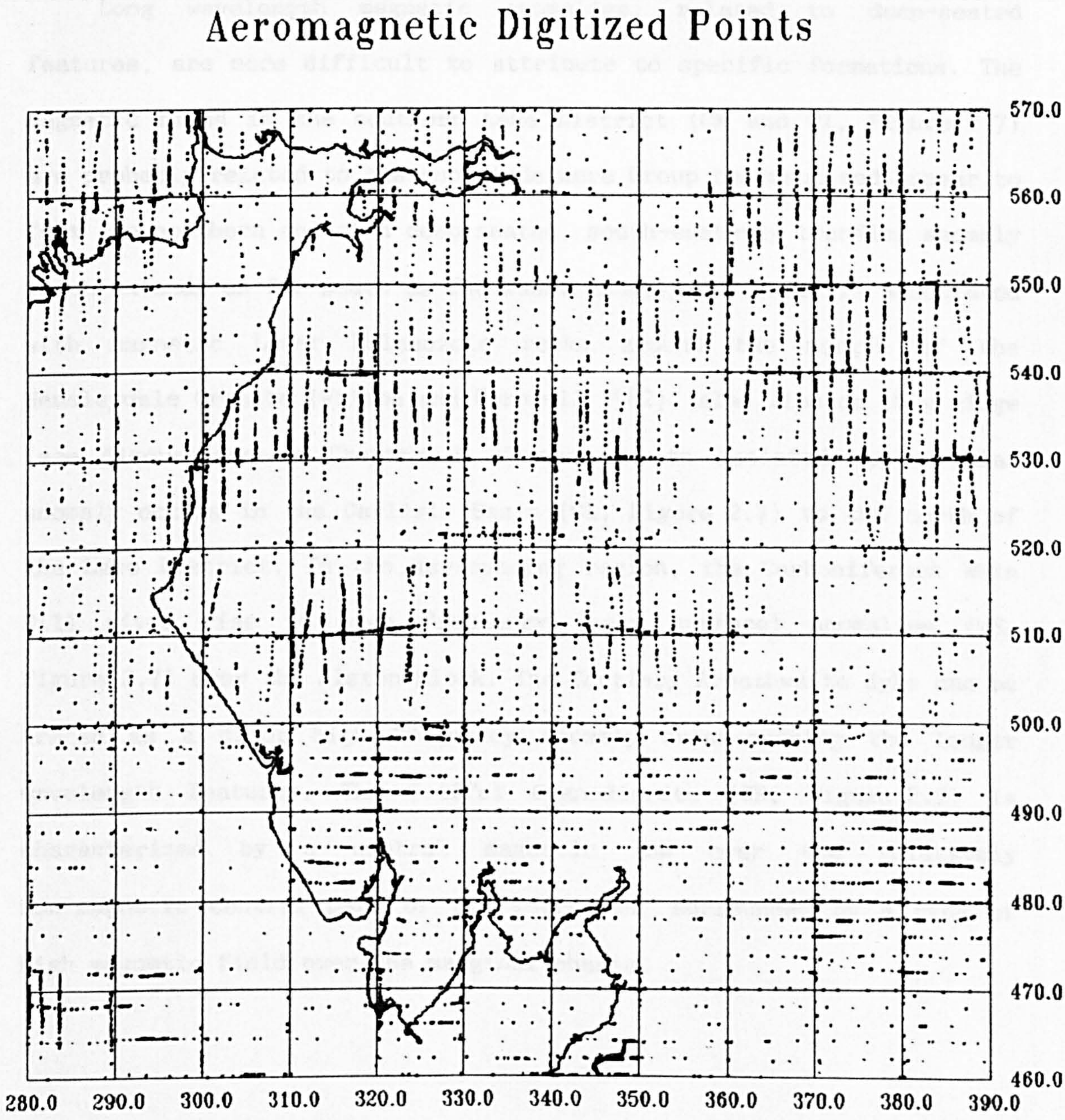


Figure 2.6 **Location of digitised aeromagnetic data points.**

District (Skiddaw, Borrowdale and Windermere groups) are relatively non-magnetic with the exception of occasional lavas in the Borrowdale Volcanic Group (Chapter 5).

Long wavelength magnetic anomalies, related to deep-seated features, are more difficult to attribute to specific formations. The magnetic highs in the southern Lake District (CM and WI, Figure 2.7) are probably related to the sub-Windermere Group basement and appear to form the northern end of a deep-seated, south-easterly trending anomaly which extends as far south as The Wash. Anomaly AB, which is associated with magnetic Lower Palaeozoic rocks around the margin of the Wensleydale Granite (Wilson and Cornwell 1982), also lies on this ridge (see discussions in Chapters 6, 7 and 8). An isolated sub-circular anomaly occurs in the Carlisle Basin (CL, Figure 2.7) to the north of the Lake District. In the surrounding region, the Carboniferous Whin Sill gives rise to high frequency (near surface) anomalies (WS, Figure 2.7) over the Alston Block. The Tertiary Armathwaite dyke can be traced as a minor high frequency anomaly cross-cutting the longer wavelength features. The Criffel Granodiorite (CR, Figure 2.7) is characterized by a central magnetic low over the relatively non-magnetic central part of the intrusion, surrounded by a ring of high magnetic field over the marginal phases.

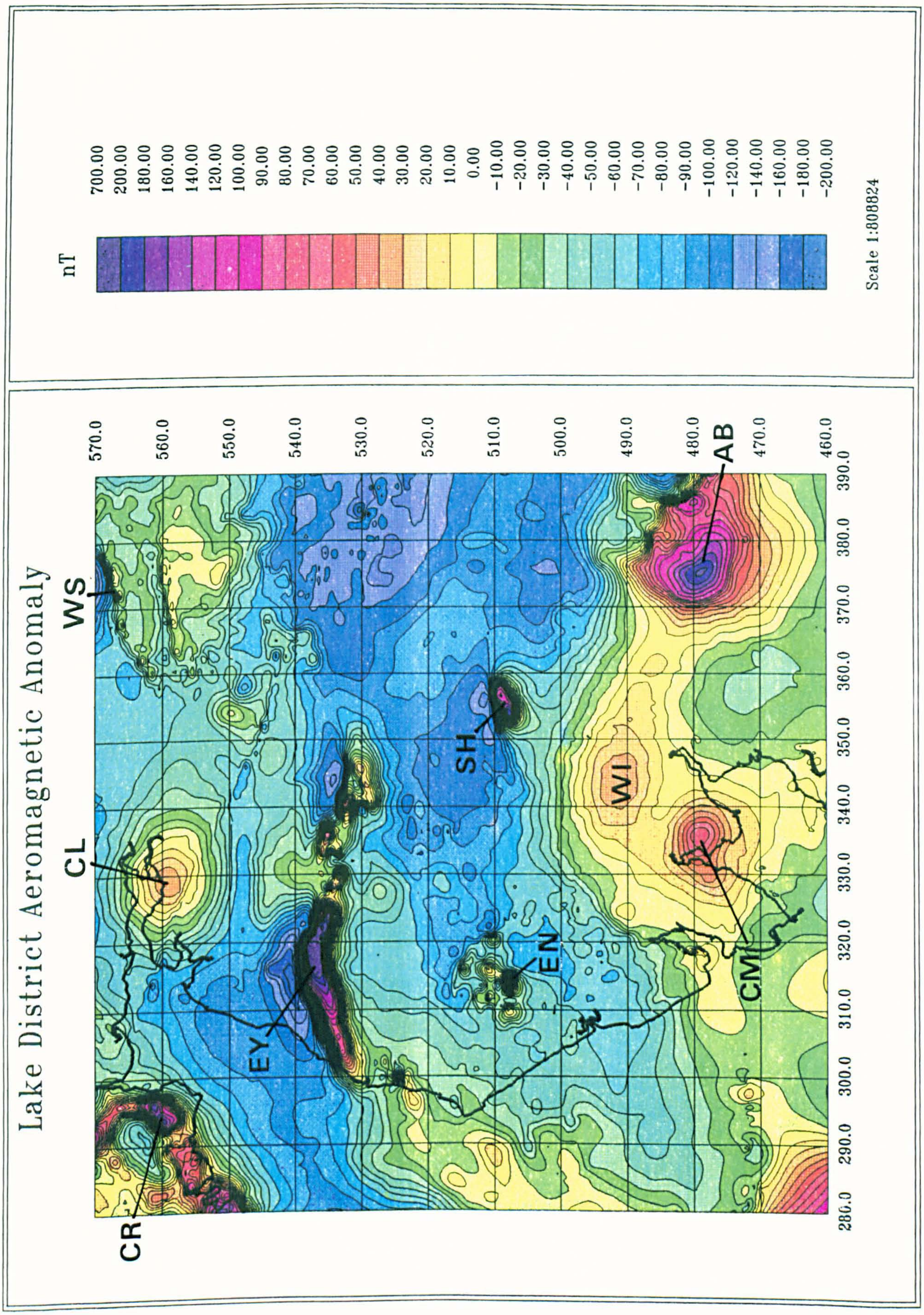


Figure 2.7 Aeromagnetic anomaly map of the Lake District based on data shown in Figure 2.6. Codes indicate anomalies as follows: EN = Ennerdale Granophyre, SH = Shap Granite, EY = Eycott lavas, AB = Askrigg Block, CR = Criffel Granodiorite, CL = Carlisle Basin High, WI = Windermere High, CM = Cartmell High, WS = Whin Sill.

CHAPTER 3

ANALYSIS OF GEOPHYSICAL LOGS FROM BOREHOLES INTO THE SHAP AND SKIDDAW GRANITES

3.1 INTRODUCTION

Heat flow boreholes approximately 300 m deep were drilled during 1982 for the HDR project (see Preface and Appendix 3) into the Shap and Skiddaw granites (in the Lake District) and the Cairngorm, Ballater, Bennachie and Mount Battock granites in the Eastern Highlands of Scotland. The holes were drilled using the down-hole rotary percussion method except for short coring runs at depths of approximately 100 m, 200 m and 300 m. A suite of geophysical logs was run in each borehole to monitor changes in the lithology between the cored sections and to investigate the physical and geothermal properties of the rocks.

The grid references of the boreholes and the drilling details are given in Appendix 4. The holes were drilled under the supervision of staff of Imperial College, London (Wheildon et al. 1984a & 1984b) and the logging was carried out under the supervision of the present author. Samples of the drill chippings from the hammered sections were collected at 5 m intervals from material washed to the surface. Determinations of the density, porosity, sonic velocity and magnetic susceptibility of selected core samples were carried out by the Engineering Geology Unit of BGS (Entwisle, 1983a, b, c and d). The results are given in Appendix 4.

Most commercial geophysical logging techniques were developed for the hydrocarbons and coal industries. The design and response of logging equipment is optimized for use in sedimentary formations and the logs are usually calibrated against sedimentary rocks. In crystalline rocks the physical properties under examination often lie beyond the calibration range of the equipment. In some cases the observed response is related to physical and chemical parameters which the logging equipment was not designed to investigate. Although commercial logging techniques have occasionally been used in crystalline rocks (e.g. McCann et al. 1982), their response and calibration varies between rock types and there are a number of uncertainties regarding their interpretation.

Procedures were developed by the author for calibrating and analysing the logs in order to examine variations in lithology, rock condition (i.e. degree of fracturing and alteration) and physical properties betweem the short cored sections. Particular objectives were to derive in-situ density values (for gravity modelling) and an indication of the variation in radiogenic heat production with depth (for subsequent heat flow modelling by the Imperial College group). This chapter describes the calibration and analysis techniques, and gives details of the results for the Shap and Skiddaw granites, which were the author's main interest in this study. The results for the four Scottish boreholes, which were analysed using the same techniques, are given in Appendix 5 for the sake of completeness. The work is published as a BGS open-file report (Lee 1984b, see Appendix 1).

3.2 LOGGING PROCEDURES AND LOG RESPONSE

The logging was carried out by British Plasterboard Ltd. under the supervision of the author. In most cases the logging was carried out before the final cored section was drilled. After completion of the logging, the boreholes (with the exception of Shap) were cased with steel pipe to reduce the effects of ground-water flow on the geothermal gradient. The following logs were run at each site: (1) The Coal Combination Sonde (CCS) which simultaneously records single-arm caliper, natural gamma, bed resolution density (BRD) and long spacing density (LSD), (2) 3-arm caliper, (3) neutron (porosity), (4) multi-channel sonic, (5) single point resistance and self-potential (recorded on separate runs using the same sonde), and (6) focussed electric (FE).

The BPB logging system, utilises a microprocessor based 'log processor unit' which is programmed to correct and compensate the raw data received from the downhole tools. The processed data were recorded onto cassettes and displayed on a chart recorder in the logging truck. Paper copies of the processed logs at a scale of 1:100 and recordings of the logs on 9 track magnetic tape were supplied to BGS. The standard BPB calibration procedures and the assumed response of the logging equipment in crystalline rocks are outlined below.

3.2.1 Caliper

The caliper is a simple mechanical device which measures the diameter of the borehole. Its main uses are to provide an accurate profile of the borehole diameter (in order to apply corrections for borehole size to other logs) and to identify zones where the sides of the borehole have collapsed (caved). Most of the logs described below are automatically compensated for changes in borehole diameter but they are not compensated for localized caving. In crystalline rocks caving usually occurs over zones of severe fracturing or alteration. These conditions in themselves produce strong responses in other logs and it is often difficult to separate the response due to caving from that due to changes in rock properties alone. When analysing other logs it is important, therefore, to bear in mind the caliper log.

Single-arm and 3-arm caliper logs were recorded in the present boreholes. The single-arm device is part of the Coal Combination Sonde and has the additional function of pushing the tool against the borehole wall. The 3-arm caliper gives a more accurate representation of changes in borehole diameter and is used as the definitive caliper log.

3.2.2 Natural Gamma

The gamma log records the level of natural radioactivity in the host rock due to the presence of the radioactive elements uranium, thorium and potassium. In sedimentary rocks it normally reflects the shale content due to the generally higher concentrations of radioactive elements in clays and shales. The BPB gamma log is calibrated with respect to the American Petroleum Institute's test pit at Houston Texas and is presented in API units. The test pit covers a range of 0 to 200 API within which the response of the logging tool is assumed to be more or less linear. The value of 200 API was designed to correspond to a shale containing 13 ppm uranium, 24 ppm thorium and 4 % potassium which are roughly twice the concentrations observed in the average American mid-continental shale. (API, 1974).

In granite the natural gamma log reflects (a) the concentrations of U, Th and K in the host rock and (b) local concentrations or deficiencies of radioactive elements in joints, altered zones and mineralized veins.

3.2.3 Density

The density log is essentially a measure of the electron density of the rock mass. A radioactive source in the logging tool emits gamma rays which collide with electrons and lose energy by Compton Scattering; the scattered gamma rays are then counted at detectors at a fixed distance from the source. The electron density is related to the bulk density of the rock which in turn depends on the density of rock matrix, the porosity of the rock and the density of the pore fluid. The volume of the rock examined depends on the source-detector spacing. BPB's Coal Combination Sonde records two channels: (1) bed resolution density (BRD) which corresponds to a short source-detector spacing (and is used to detect small-scale lithological variations in sedimentary rocks) and (2) long spacing density (LSD) which records the bulk (saturated) density of the rock.

In the case of boreholes into granitic rock the bulk density as recorded by the LSD log is of most interest. The log is recorded initially in BPB 'standard density units' and is corrected for borehole diameter (from the caliper log) and background gamma radiation (from the natural gamma log). The response is then 'calibrated' and presented to the customer as a 'linear density log' in Mg/m^3. The tool is designed essentially for low density coal lithologies and the results are considered to be unreliable in high density crystalline rocks; BPB recommend that in these circumstances the log is calibrated against borehole samples (see Section 3.3.2).

3.2.4 Neutron

In sedimentary rocks neutron logs are used principally for the delineation of porous formations and for the determination of their porosity. The equipment responds primarily to the amount of hydrogen present in the formation. High energy neutrons emitted from a radioactive source collide with nuclei in the rock mass, losing energy with each collision. The greatest energy loss occurs when the neutrons collide with bodies of similar mass such as hydrogen nuclei. Eventually the neutrons are slowed by successive collisions to thermal velocities when they diffuse randomly without losing further energy until they are captured by the nuclei of atoms such as chlorine, hydrogen and silicon. When the hydrogen concentration of the material surrounding the neutron source is large most of the neutrons are slowed down and captured within a short distance; when the hydrogen concentration is small the neutrons travel further from the source before being captured. Variations in response at the neutron detector, therefore, reflect variations in the hydrogen content of the rock.

In sedimentary formations, where the rock pores are filled with water or oil, the neutron log reflects the amount of liquid-filled porosity. In fresh crystalline rock the porosity is usually very low (close to the detection limit of the equipment) and the log is likely to respond primarily to water within joints and fracture zones. In altered crystalline rocks the response is more complex. Altered sections might be expected to have a higher true porosity than fresh rock but the equipment will also respond to hydrogen atoms within crystal lattices (i.e. OH associated with alteration products) which do not represent true porosity.

The BPB neutron logs are recorded initially in 'standard neutron units'. They are subsequently corrected for borehole diameter (from the caliper log), calibrated against a particular rock matrix and presented to the customer as true porosity logs (in per cent). As BPB are unable to calibrate against a granite rock matrix the present logs were calibrated against limestone. This has resulted in a systematic error (i.e. a shift of the zero porosity line) on some logs due to the difference in response between limestone and the various crystalline lithologies encountered.

3.2.5 Multichannel sonic

The multichannel sonic log records the interval transit time (i.e. the reciprocal of velocity) of a compressional sound wave between a source and series of receivers mounted in the logging tool. In sedimentary rocks sonic logs are used for the determination of porosity and as an aid to the interpretation of seismic records. In clean sedimentary formations with intergranular porosity (such as sandstone) there is a linear relationship between porosity and transit time. An accurate value of the porosity can be calculated if the transit times of the rock matrix and pore fluid are known. In rocks where intergranular porosity is not the dominant factor (i.e. in fractured rock) the relationship between the porosity and sonic velocity is more complex and calculations based on the sonic log will not yield the true porosity.

In fresh crystalline rock the sonic log responds to changes in lithology and to fractures (which are characterized by a sharp decrease in the sonic velocity). In altered crystalline rock the sonic velocity is lower and generally much more variable.

The BPB sonic logging tool has four channels corresponding to different source-receiver spacings. The long spacing channel (channel 3, 610 mm) gives the best average formation velocity and is the one referred to in discussions below.

3.2.6 Resistance and focussed electric

Single point resistance and focussed electric logs record changes in the electrical resistivity of the rock mass. In the oil industry they are used mainly to investigate porosity and hydrocarbon saturation. In fresh crystalline rocks the resistivity is generally very high, often close to the upper working limit of logging equipment. At these high resistivities changes in lithology and small changes in porosity have relatively little effect. The main influences on the logs are fractures, alteration and mineralization, all of which cause a reduction in the measured apparent resistivity.

Both single point resistance and focussed electric (FE) logs were run in the heat flow boreholes. The focussed electric tool has a far greater depth of investigation and the results are calibrated to give rock resistivities in ohm-metres. The single point resistance log gives only a qualitative indication of changes in resistivity. In addition the response of the single point equipment was observed to be unpredictable and sometimes inverted at high resistivities. For these reasons the single point logs were not used in the analysis.

3.2.7 Spontaneous potential

The spontaneous potential (SP) log records the natural potentials developed between the borehole fluid and the surrounding rock mass. In sedimentary rocks SP logs are used mainly for the detection of permeable beds, the location of their boundaries and for correlation between adjacent boreholes. The natural potentials measured by the SP log are caused by electrical currents in the borehole fluid arising from electromotive forces (of both electrochemical and electrokinetic origin) in the surrounding rock mass. In sedimentary rocks, the movement of ions which gives rise to the SP phenomenon is possible only in formations with a certain minimum permeability but there is no direct relationship between the magnitude of the SP deflection and either the formation permeability or porosity. In crystalline rocks SP anomalies are related in a complex way to zones of fracturing, alteration and mineralization. The BPB SP log is uncalibrated and presented on an arbitary scale.

3.3 PRESENTATION OF RESULTS AND CALIBRATION AGAINST BOREHOLE SAMPLES

Copies of the logs in digital form were supplied to BGS on magnetic tape and analysed on the Survey's GEC 4090 computer. The WELOG package of computer programs (Jones & Wiseman 1981) was used to plot the logs at A4 scale and to convert them to SI units where appropriate. An additional computer program was written by the author to generate logs of 'calibrated density', 'estimated heat production' and 'lithology and rock condition', and to plot histograms and crossplots of the log data. The procedures used to calculate the derived logs are described below.

3.3.1 Estimated heat production log

Accurate determinations of the uranium and thorium content of selected core samples were made by the Open University group using instrumental neutron activation analysis (INAA). Although the method produces accurate individual values of heat production there is sometimes considerable variation within each core and between the cored sections. These are due partly to genuine local variations in the concentration of radioactive elements and partly to problems associated with taking representative samples in uraninite-bearing rocks (Webb & Brown 1984a and 1984b). The cored sections themselves represent less than 10 % of the total depth of each borehole, over the remaining 90 % the heat production could be estimated only from the chippings washed to the surface during hammer drilling. The results show large variations between each 5 m section and generally underestimate the heat production as determined from the core (Webb & Brown 1984a and 1984b; Wheildon et al. 1984a and 1984b).

The natural gamma log is not designed to measure heat production. The log does not distinguish between the various radioactive elements present in the rock and records only the level of their combined activity. The response of the logging tool is a complex function of borehole and host-rock conditions which makes it difficult to relate log readings (in API units) to the actual concentrations of radioactive elements present in the rock, and thus to heat production. However Rybach et al. (1982) have shown that in an analogous situation (the Gotthard tunnel) it is possible to calibrate a portable scintillation counter against rock samples in order to estimate heat production away from the sample sites. Successful calibration was only possible in this case because both the Th/U ratio and the geometry of the tunnel remained fairly constant. Rybach et al. (1982) also point out that the zero intercept of the calibration line will vary significantly from one tunnel to another if the ventilation conditions, and thus the background radon levels, are different.

In view of the poor control between the cored sections of the heat flow boreholes it was considered worthwhile attempting to calibrate the gamma logs against laboratory heat production determinations in order to derive heat production logs. The accuracy of the resulting logs depends critically on several factors:

(1) **That the response of the logging tool is roughly linear over the full range of values observed.** The response is stated to be linear in the range 0-200 API and is assumed to be linear above that range. However BPB Ltd. are not able to supply calibration data to support a linear response above 200 API.

(2) **That the relative proportions of U and Th (and to a lesser extent K) remain fixed throughout the borehole.** Except in the most uniform lithology this condition is unlikely to be met. However the resulting errors are acceptable over a surprisingly wide range of variations. This is because the gamma log records the total activity of the rock mass (above a level of approximately 100 keV) and the relative contribution of U and Th to this total activity is roughly in proportion to their contribution to the heat production. U, Th and K are responsible for the emission of 2.8 x 10^4, 1 x 10^4 and 3.4 gamma-rays/s/g respectively of energies greater than 100 keV (Belknap et al. 1959). The heat production per unit mass (A_m) of a rock is given by:

$$A_m = 0.1326\ (0.718\ U_{ppm} + 0.193\ Th_{ppm} + 0.262K_{\%})$$

These coefficients have been used to calculate the error with respect to a Th/U ratio of 2. The results (Figure 3.1.) show that

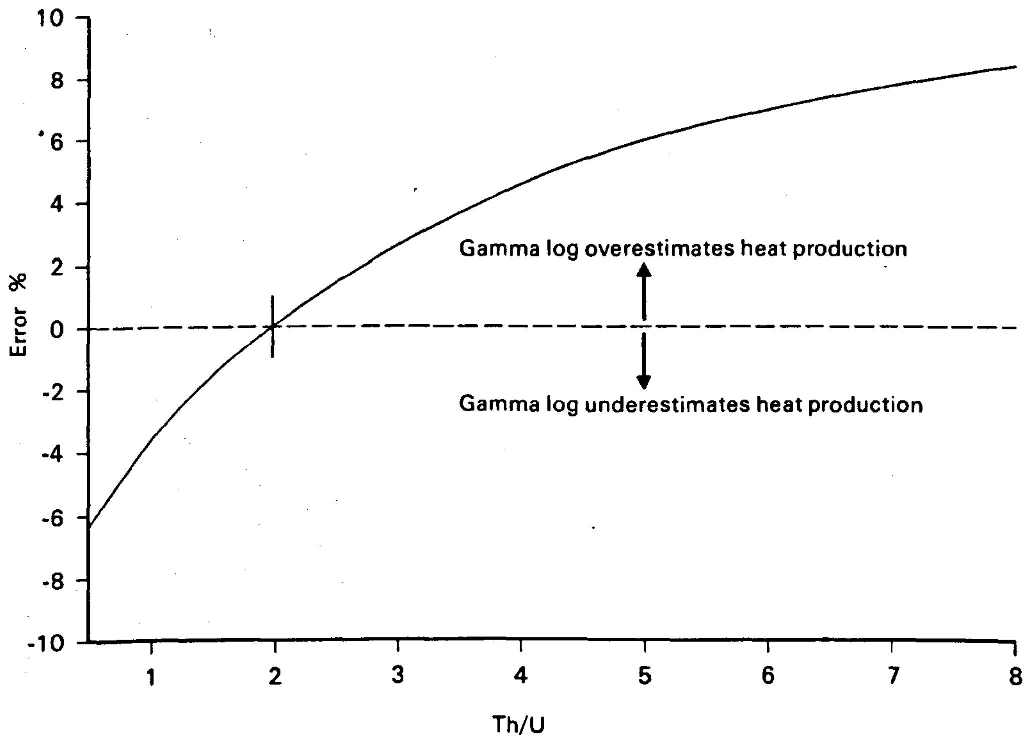


Figure 3.1 The effect of variations in the Th/U ratio on the accuracy of heat production estimates from the natual gamma log.

the error is less than +/- 9 % for ratios within the range 0.5 to 8. Only zones of mineralization or severe alteration would be expected to lie outside this range.

(3) That the U and Th decay series are in secular equilibrium. Gamma rays are produced at several stages in the decay series. The U-series equilibrium in particular is easily disturbed by radon migration (i.e. the influx of radon-rich or radon-depleted groundwater). The significance of radon migration is difficult to establish but the possibility of disturbance from this source should be borne in mind when analysing the logs.

(4) That there are no major variations in the concentration of heavy elements which would change the absorptive characteristics of the rock mass.

The data used to calibrate the gamma logs are given in Appendix 4 (Table A4.3) and plotted on Figure 3.2, together with the regression lines applicable to each borehole. The lines were all forced through a point at (-23,0) which is the implied origin of the API calibration line (Belknap et al. 1959). The data show a considerable degree of scatter. In addition to the factors affecting the gamma logs outlined above, the scatter also reflects the fact that the two parameters being plotted (i.e. heat production from core samples and gamma count from the logs) represent the activity from different volumes of rock. Moreover, the core data represent the freshest, least jointed, rock whilst the gamma count records the in-situ activity which incorporates the response from zones with anomalous concentrations and depletions of radioactive elements. These factors could be particularly important

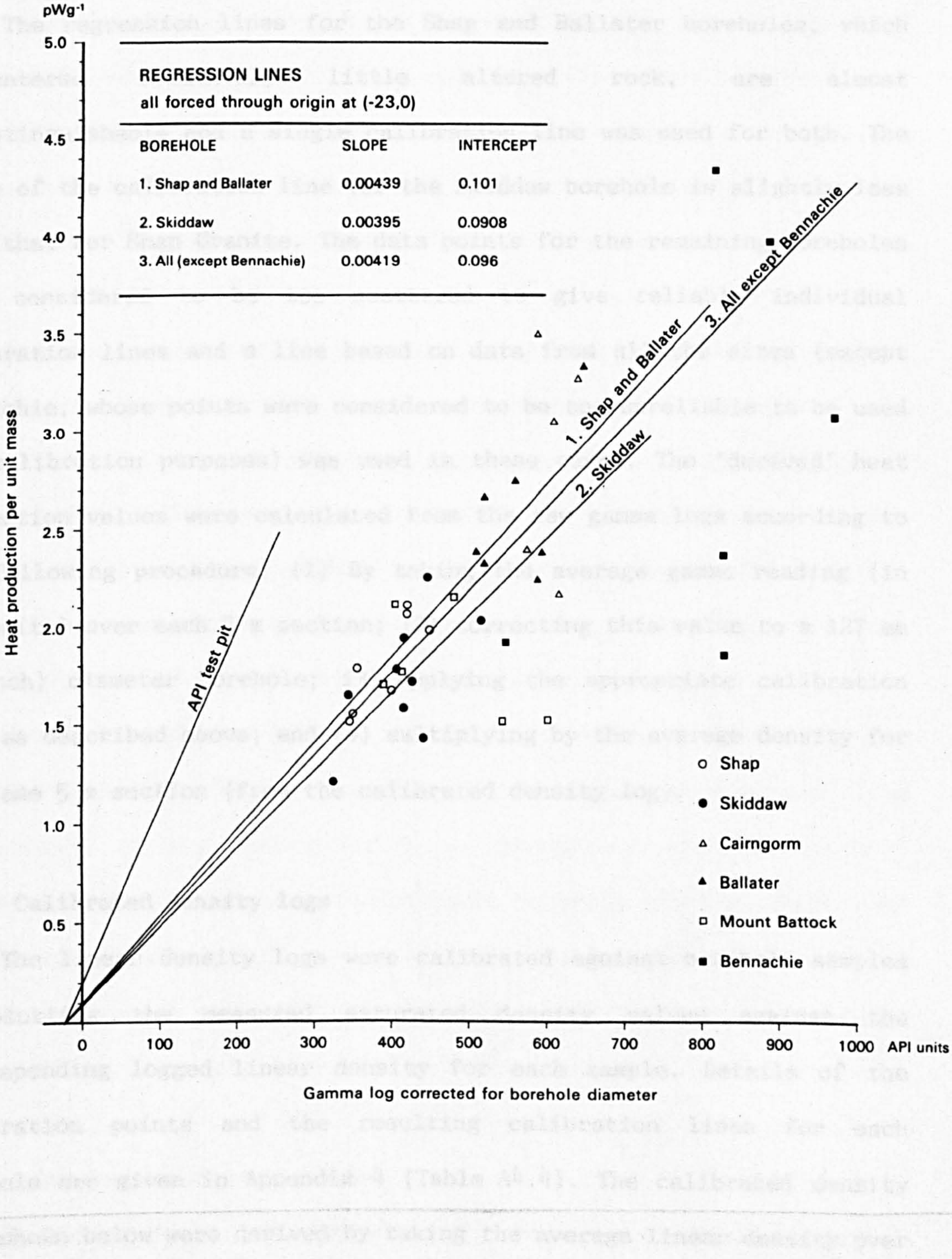


Figure 3.2 Heat Production calibration lines

where the rock type, intensity of jointing and degree of alteration are variable.

The regression lines for the Shap and Ballater boreholes, which encountered relatively little altered rock, are almost indistinguishable and a single calibration line was used for both. The slope of the calibration line for the Skiddaw borehole is slightly less than that for Shap Granite. The data points for the remaining boreholes were considered to be too scattered to give reliable individual calibration lines and a line based on data from all the sites (except Bennachie, whose points were considered to be too unreliable to be used for calibration purposes) was used in these cases. The 'derived' heat production values were calculated from the raw gamma logs according to the following procedure: (1) By taking the average gamma reading (in API units) over each 5 m section; (2) correcting this value to a 127 mm (5 inch) diameter borehole; (3) applying the appropriate calibration line as described above; and (4) multiplying by the average density for the same 5 m section (from the calibrated density log).

3.3.2 Calibrated density logs

The linear density logs were calibrated against borehole samples by plotting the measured saturated density values against the corresponding logged linear density for each sample. Details of the calibration points and the resulting calibration lines for each borehole are given in Appendix 4 (Table A4.4). The calibrated density logs shown below were derived by taking the average linear density over each 5 m section and applying the appropriate calibration line. The results were not corrected for local caving.

3.3.3 Lithology and rock condition logs

The conjectural lithology logs represent an attempt to define the lithology between the cored sections. The logs were derived by making a qualitative comparison between the response of the various logs over the cored sections and their response over the uncored sections. It should be noted that the difference in response between one crystalline rock and another is often quite subtle and the imprint of alteration and jointing tends to obscure the effects of lithological changes.

The rock condition logs represent an attempt to describe the state of alteration and jointing between the cored sections. The results were derived from the focussed electric logs which are the most sensitive to the presence of fracturing and alteration. The average resistivity was calculated for each 1 m section of borehole and the 'rock condition' was defined according to two or three broad categories. The rock condition ascribed to each resistivity band varies from one borehole to another because of the different lithologies and borehole conditions. It is worth noting that the focussed electric log is more sensitive to small zones of low resistivity (i.e. joints and veins) in a high resistivity (i.e. fresh rock) matrix than to small bands of fresh rock in a generally altered or jointed section. The rock condition log will therefore tend to underestimate the amount of fresh rock in altered zones.

3.3.4 Histograms and cross-plots.

Histograms and cross-plots of estimated heat production, calibrated density, limestone porosity, resistitvity and sonic velocity were generated for each borehole. Each 'sample' in these plots represents the average value over a 1 m section of a borehole. In the case of the cross-plots different symbols have been used for sections with identifiably distinct properties.

3.4. RESULTS FOR THE SHAP BOREHOLE

The raw geophysical logs, expanded logs over the cored sections, and derived logs are shown in figures 3.3, 3.4 and 3.5 respectively. Histograms and cross-plots of the log response are shown in figures 3.6 and 3.7 respectively. The core was examined in detail by P.C. Webb (Open University) and the descriptions shown on the figures are taken from Webb & Brown (1984a). The upper core consists of coarse pink porphyritic granite (typical 'Shap' granite) with few joints. The middle core consists of medium-grained grey granite with some minor joints. The lower core is similar to the upper core but is partially haematized, jointed and mineralized.

The uniformity of the raw geophysical logs (Figure 3.3) suggests that the lithology and rock condition vary little down the borehole except over the grey granite intersected by the middle core. The grey granite is characterized by slightly higher density, higher sonic velocity, lower natural gamma count and higher porosity. The first three of these characteristics would be expected of a rock which is slightly more basic than the normal pink granite (Webb & Brown 1984a) but the higher 'porosity' almost certainly reflects the effects of a different rock matrix on the neutron porosity tool (see porosity determinations tabulated in Appendix 4, Table A4.2). Taken together the logs suggest that the grey granite extends between about 184 and 217 m (Figure 3.5).

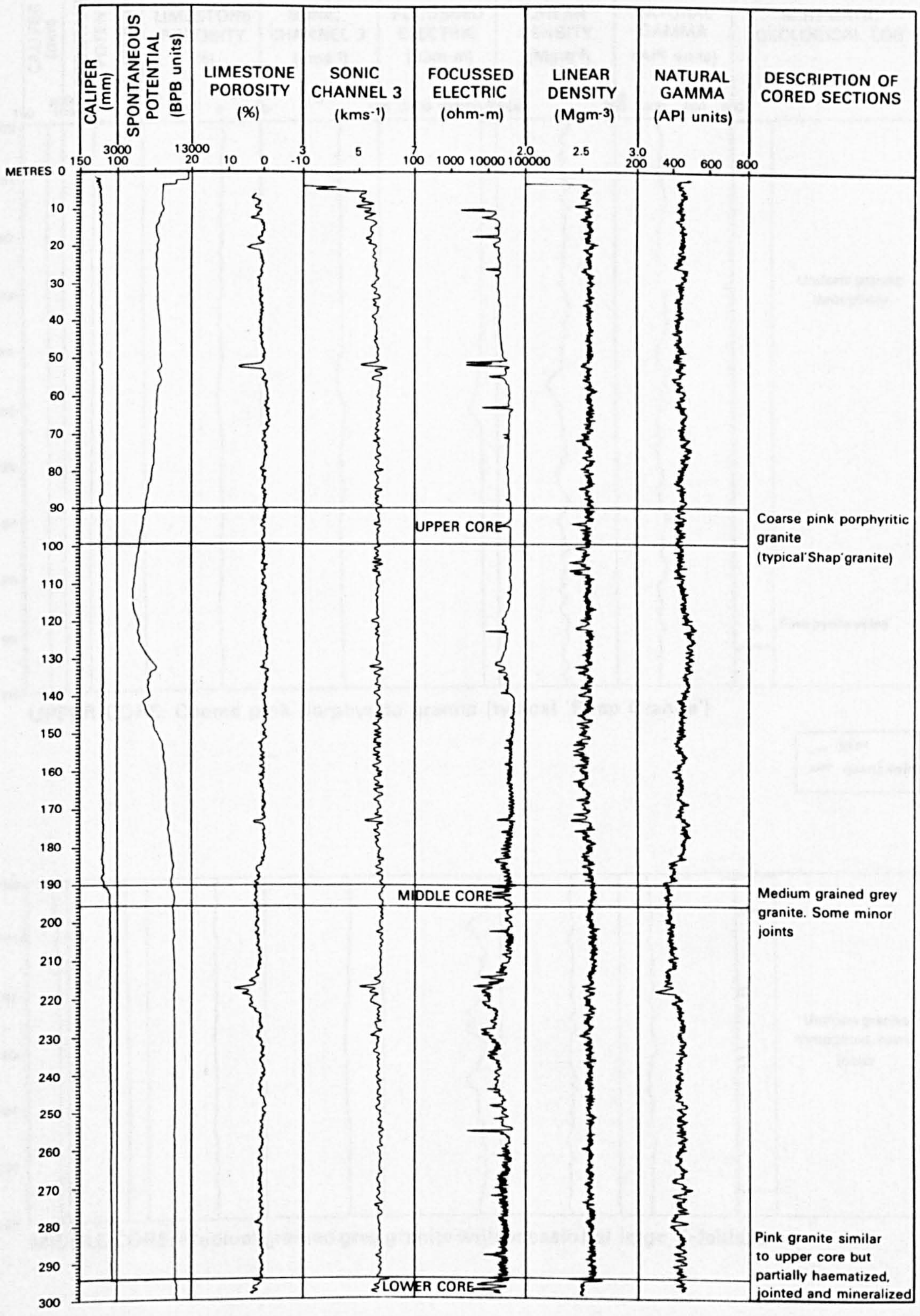


Figure 3.3 **Shap borehole: geophysical logs.**

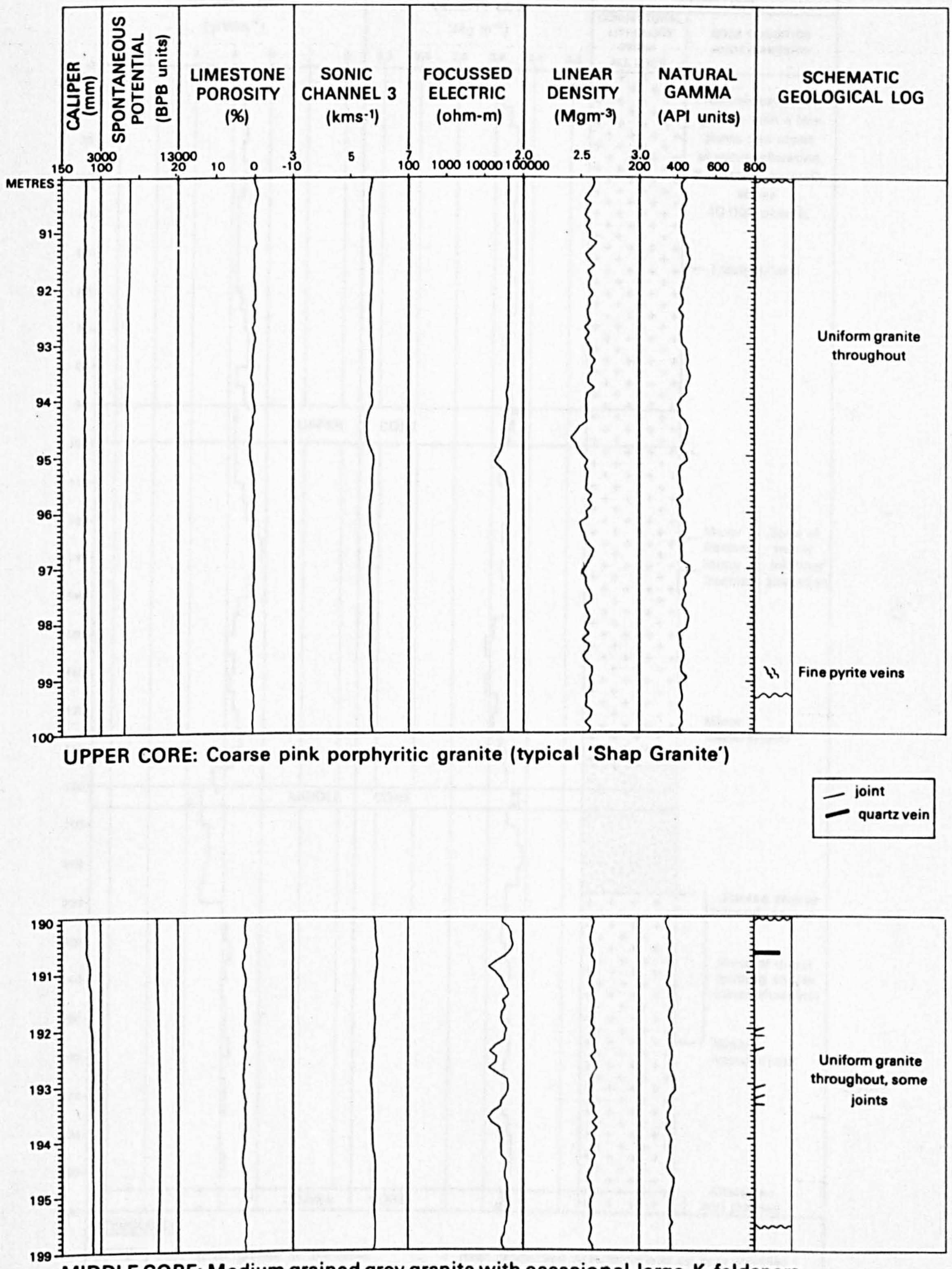


Figure 3.4 Shap borehole: expanded logs over the upper and middle cored sections.

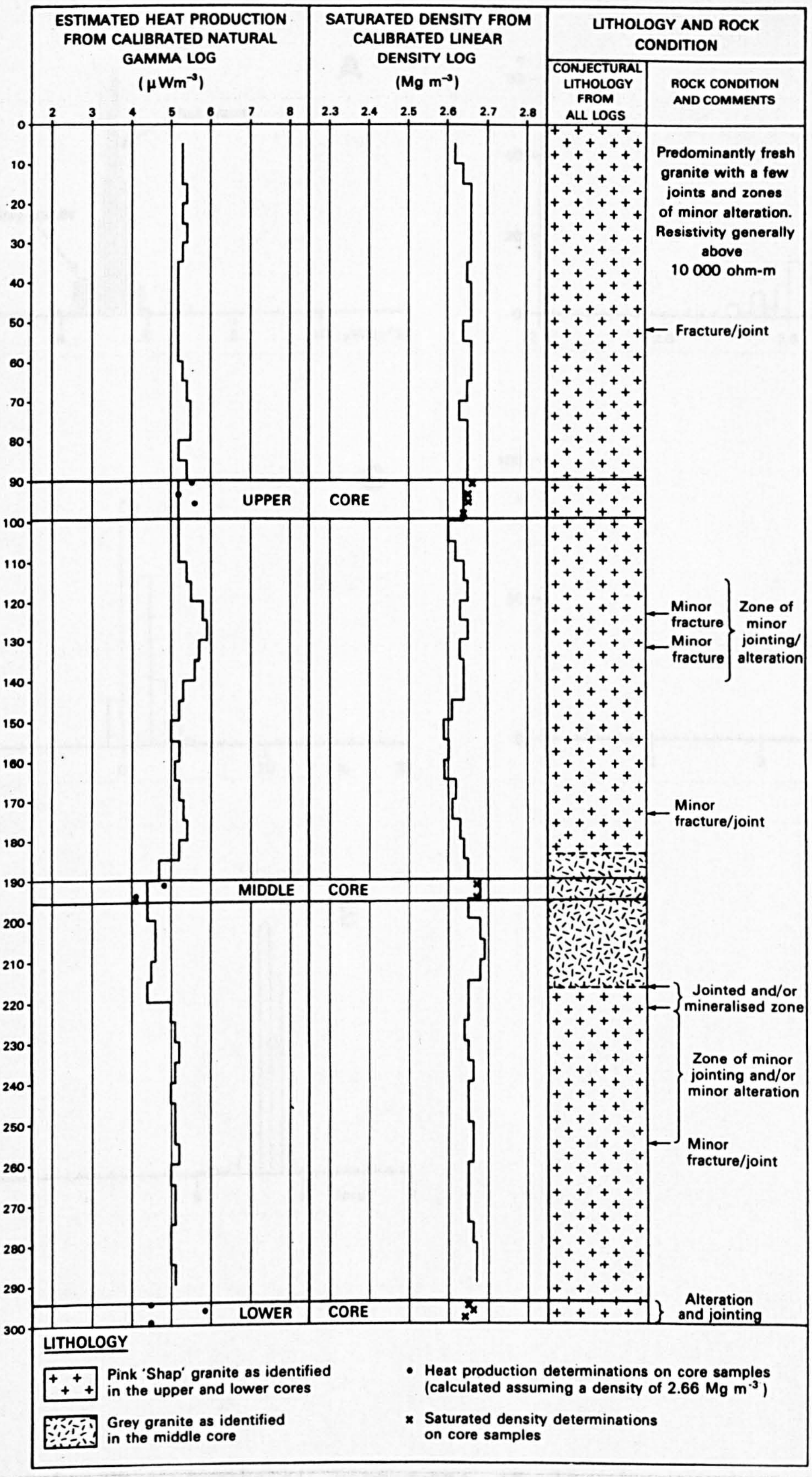


Figure 3.5 **Shap borehole: derived logs.**

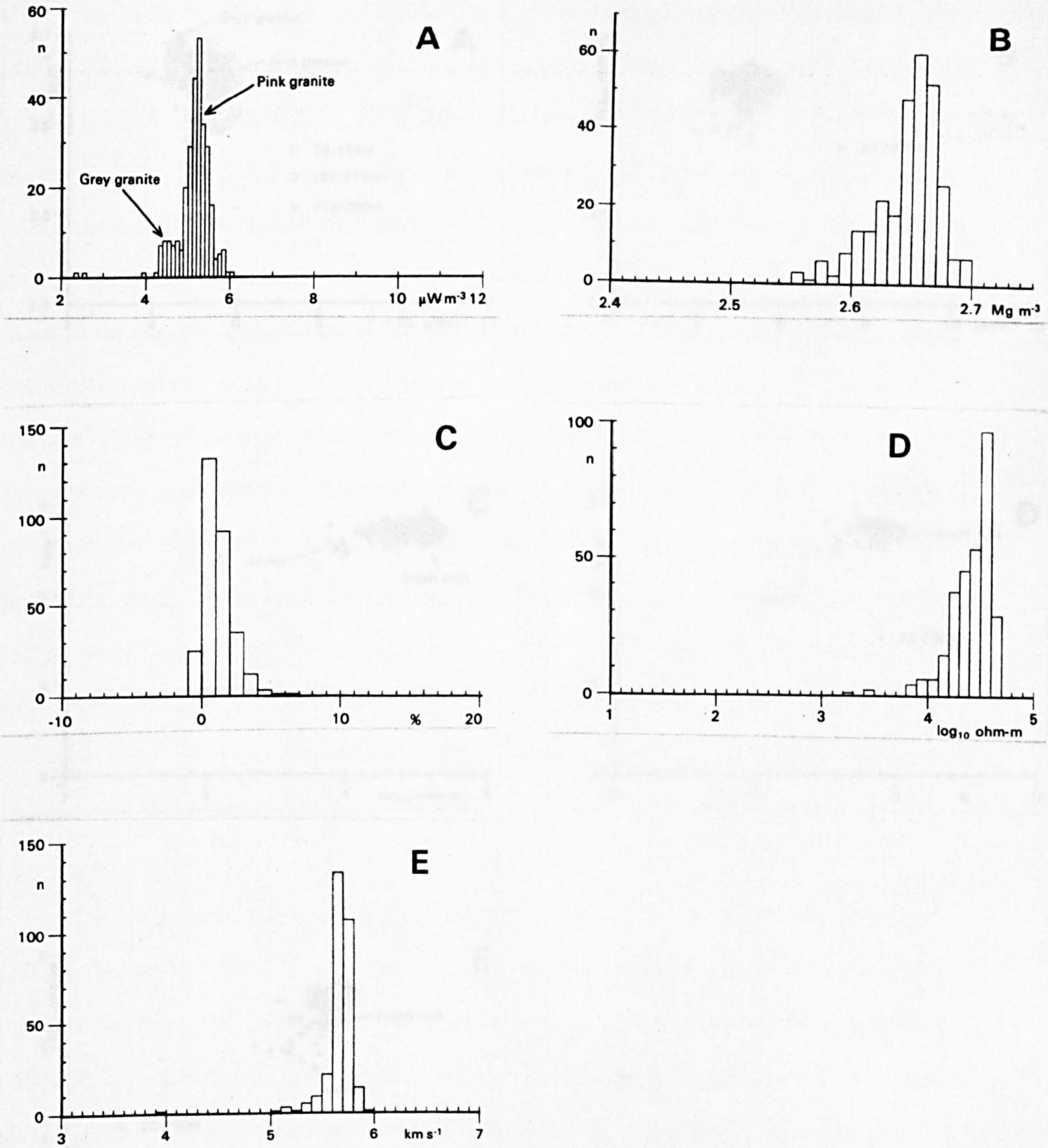


Figure 3.6 Shap borehole: histograms of log response. A = heat production, B = calibrated saturated density, C = 'limestone porosity', D = resistivity, E = sonic velocity. Each 'sample' represents the mean logged value over a 1 m section of the borehole.

The logs indicate the presence of a number of narrow fracture zones or mineralized veins characterized by sharp decreases in sonic velocity and resistivity, and increases in porosity. The most prominent occur at 52, 132, 173 m and near the base of the grey granite (217 m). A number of minor fractures are also indicated by the FE log but these do not show up on either the sonic or porosity logs. The FE and SP logs show a zone of disturbance between about 110 and 140 m which also coincides with a slightly higher natural gamma count. This might indicate the presence of a separate granite phase or perhaps some minor jointing or alteration. A further zone of minor jointing or alteration between the base of the grey granite and 255 m is apparent from the FE log. The high frequency variation observed on the FE log below about 150 m is instrumental in origin and is due to the fact that the logging tool is working at resistivities well above its design limit. The general form of the log is probably correct but the detail should be considered suspect.

The expanded logs over the upper cored section (Figure 3.4) are particularly uniform. Some fine pyrite veins near the base of the core appear to have no effect on the geophysical logs. The most prominent feature is the sharp deflection on the focussed electric log at about 95 m with nearly coincident anomalies on the sonic and density logs. These effects are presumably due to a nearby joint or vein which is not represented in the core. The middle core section has a greater number of joints and veins which are detected principally by the focussed electric log.

The heat production calibration is reasonably well constrained and the laboratory determinations bracket the range of values shown on the log (Figure 3.5). The log suggests that the average in-situ heat production of the pink granite is about 5.3 $\mu W/m^3$ in the upper part of the borehole (above 184 m) and about 5.1 $\mu W/m^3$ below 220 m. The average in-situ value for the grey granite is about 4.5$\mu W/m^3$. The calibrated density log reflects the slightly higher density of the grey granite (about 2.68 Mg/m^3) compared with about 2.65 to 2.66 Mg/m^3 for the pink granite and shows a slight increase in density toward the base of the borehole.

The histograms and cross-plots (Figures 3.6 and 3.7 respectively) reflect the uniform nature of the rock. The estimated heat production histogram (Figure 3.6a) clearly shows a group of lower than average values corresponding to the grey granite. The cross-plot of heat production against density (Figure 3.7a) shows separate populations corresponding to the pink and grey granite varieties. The other cross-plots show tight clusters of points representing fresh unjointed rock with a few points of lower resistivity, lower sonic velocity and higher porosity which correspond to joints.

3.5. RESULTS FOR THE SKIDDAW BOREHOLE

The core was examined in detail by P.C. Webb (Open University) and the descriptions below (and those shown on the figures) are taken from Webb & Brown (1984a). The upper core consists of white biotite granite, the middle and lower cores of grey biotite granite. Only 20-30 % of the core material is relatively fresh and even this often appears partially altered with some biotites replaced by chlorite (or chlorite and muscovite), and plagioclase feldspars mildly sericitized. In the altered granite (70 - 80 % of the core material) all biotite has been replaced by muscovite or chlorite and almost all plagioclase by sericite. The most intense alteration is observed close to veins of calcite or ankerite.

The raw geophysical logs (Figure 3.8) show considerably more variation and a much wider range of values than those from the Shap borehole, reflecting the generally altered and fractured nature of the granite. The caliper log shows a number of zones where the borehole has caved, presumably as a result of severe alteration or fracturing. The proportion of fresh rock, as indicated by high resistivity, low porosity and high sonic velocity, is relatively small and the zones of alteration appear to get wider towards the bottom of the borehole.

The expanded logs over the upper cored section (Figure 3.9) clearly illustrate the difference in response between fresh and altered rock. The focussed electric log shows the most marked response with resistivities of around 10000 ohm-metres in fresh granite and less than 1000 ohm-metres in altered granite. The sonic velocity log records values of about 5.7 km/s in fresh rock and less than about 5.4 km/s in altered rock. The porosity log records values close to zero in fresh granite and greater than about 5 % in altered rock. Over the middle cored section the logs reflect the higher proportion of altered granite; the resistivity is generally below 1000 ohm-metres and the small zone of fresh rock at around 179 m is not sufficiently extensive to be resolved in the low resistivity background.

The rock condition log (Figure 3.10) gives an estimate of the relative proportions of fresh and altered granite over the full depth of the borehole. It suggests that the middle core has intersected a broad transition zone between relatively fresh granite (167 - 175 m)

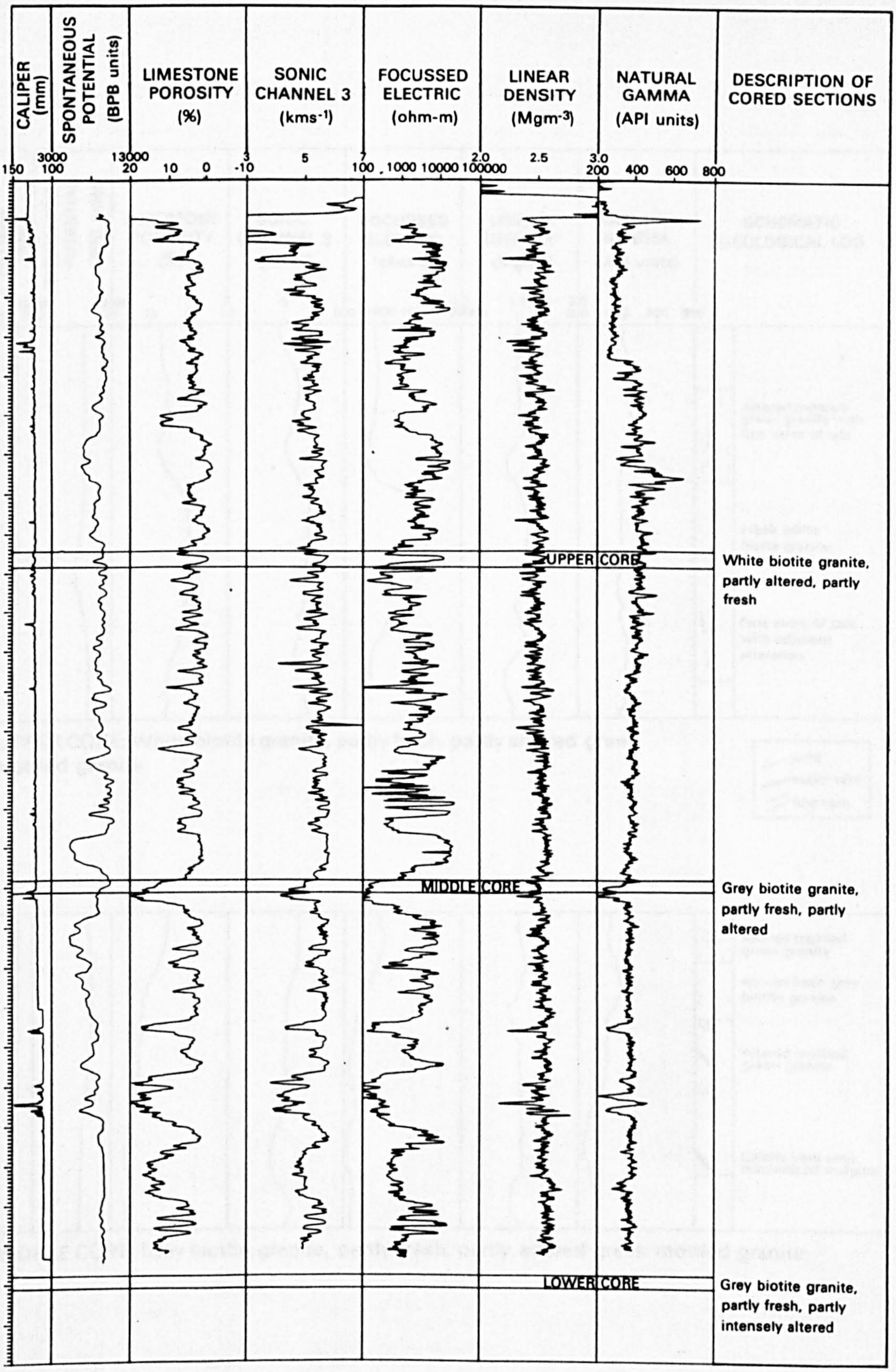


Figure 3.8 **Skiddaw borehole: geophysical logs.**

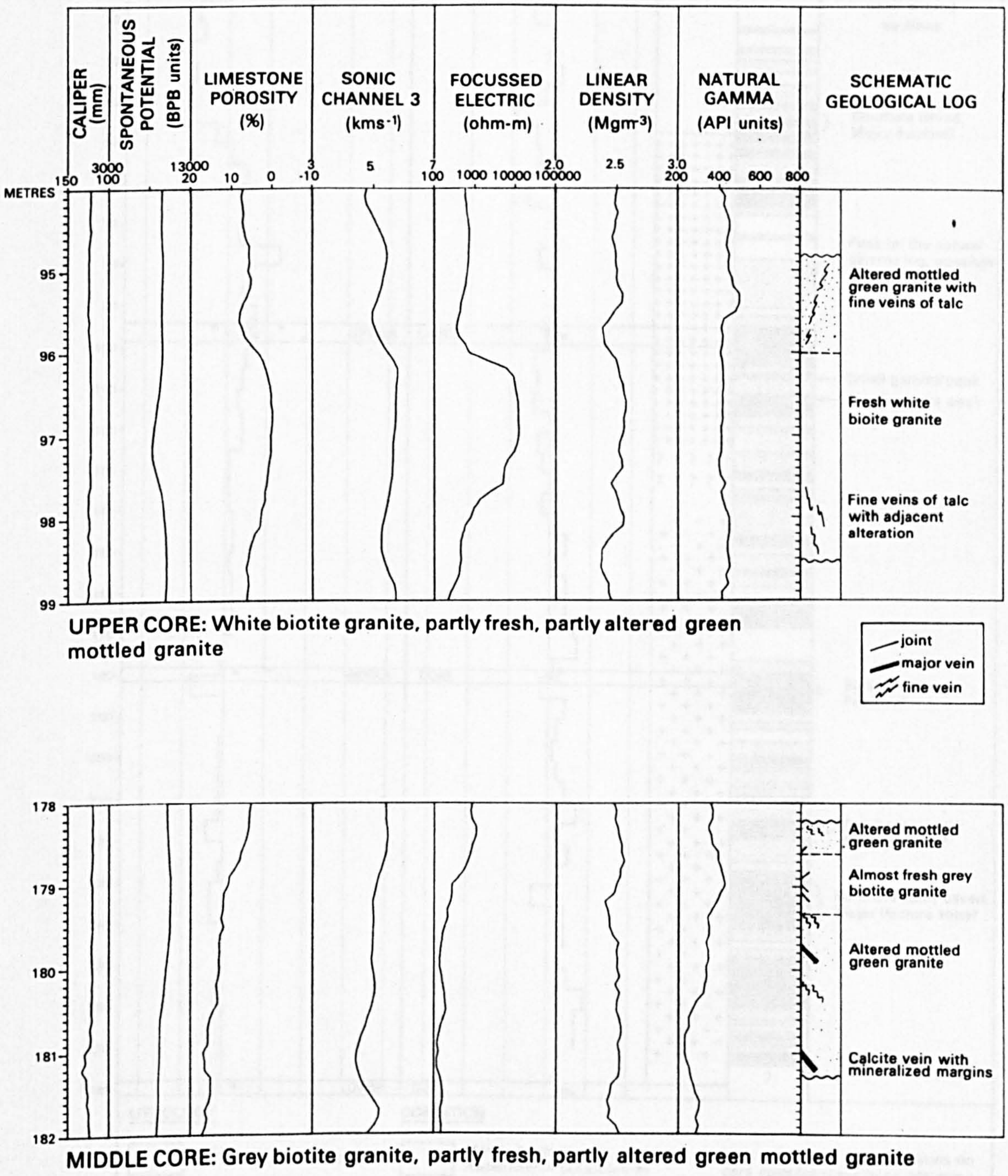


Figure 3.9 Skiddaw borehole: expanded logs over the upper and middle cored sections.

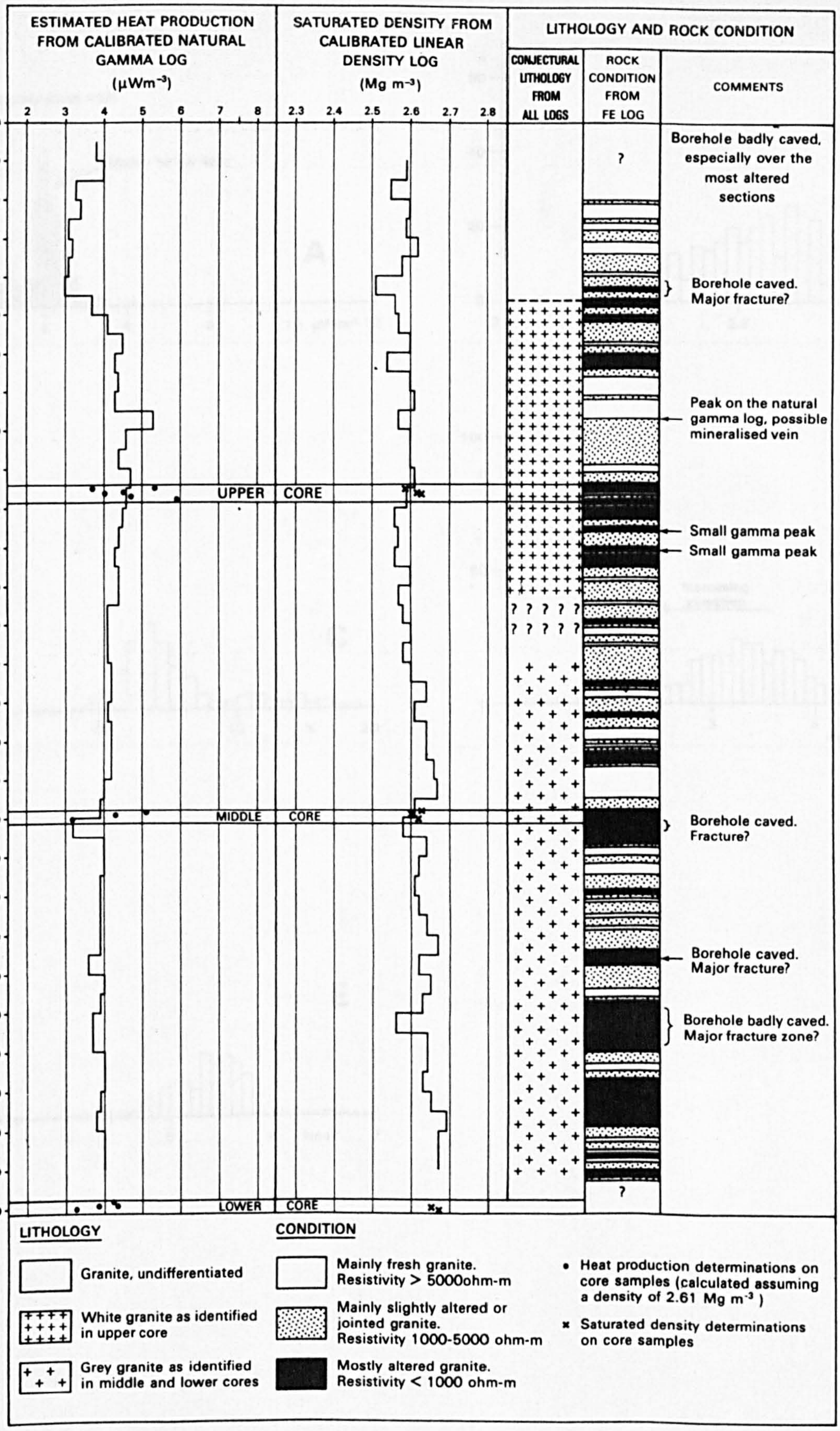


Figure 3.10 Skiddaw borehole: derived logs.

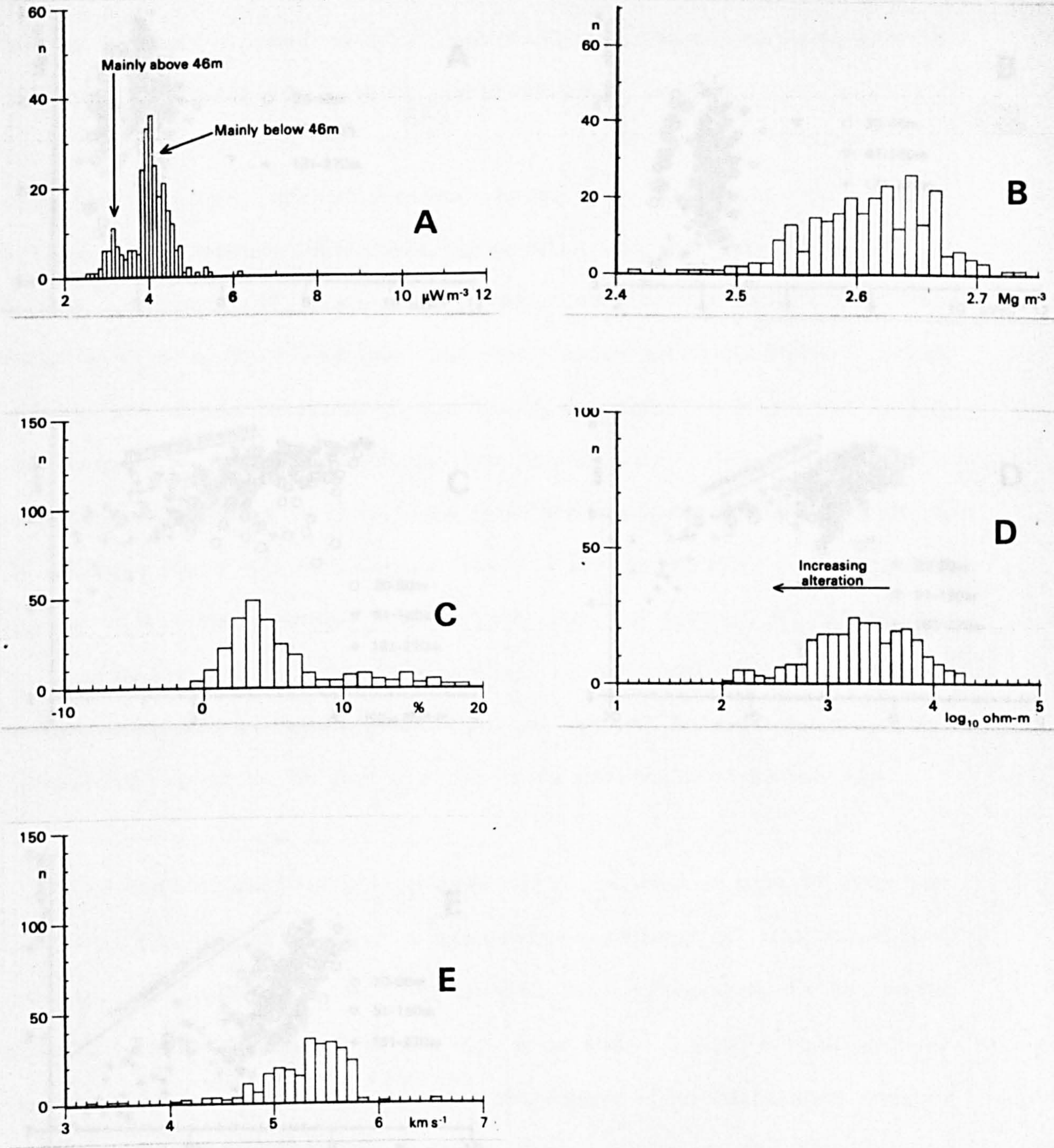


Figure 3.11 Skiddaw borehole: histograms of log response. A = heat production, B = calibrated saturated density, C = 'limestone porosity', D = resistivity, E = sonic velocity. Each 'sample' represents the mean logged value over a 1 m section of the borehole.

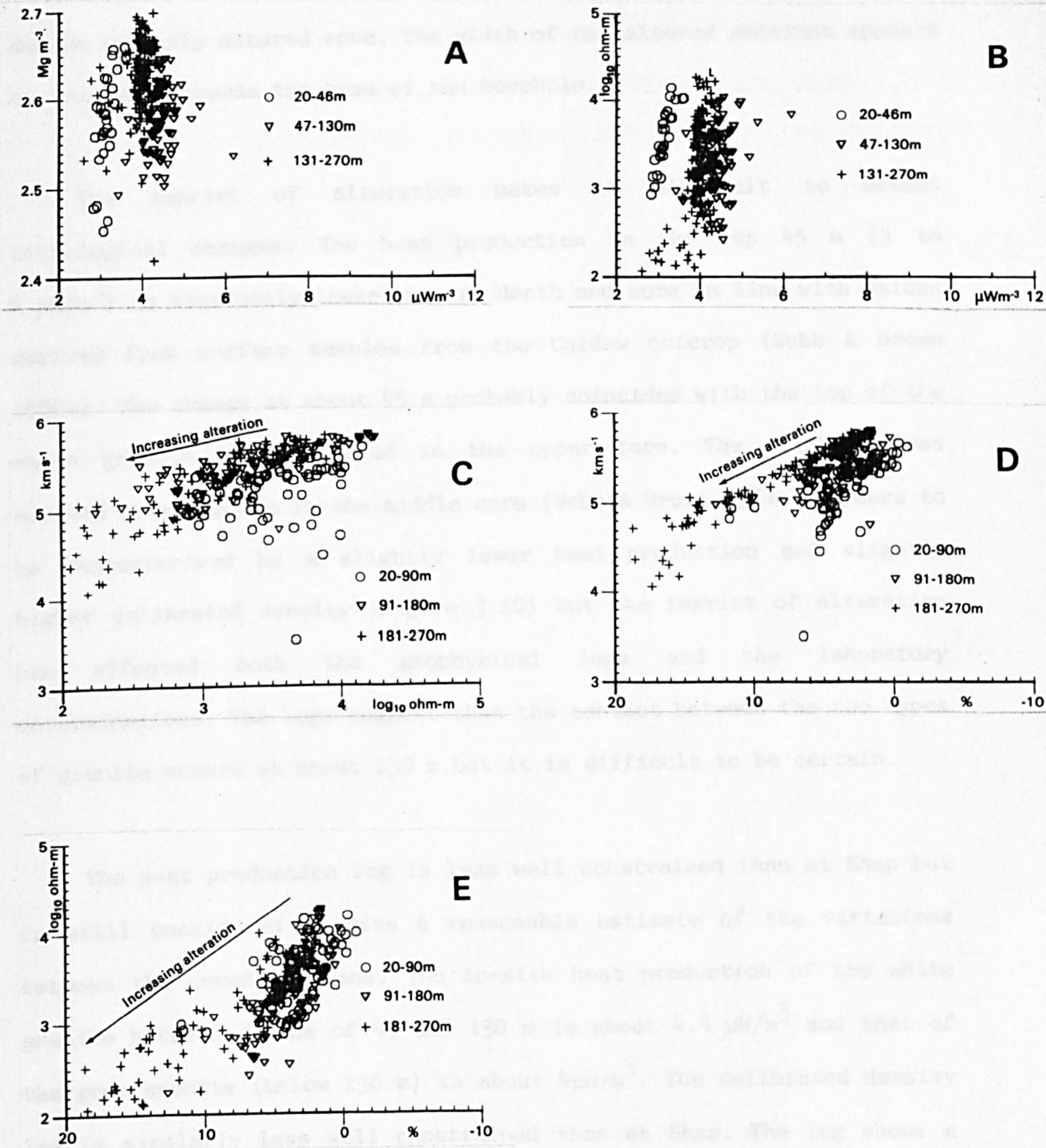


Figure 3.12 **Skiddaw borehole: cross-plots of log response. A = heat production against density, B = heat production against resistivity, C = resistivity against sonic velocity, D = porosity against sonic velocity, E = porosity against resistivity.**

and an intensly altered zone. The width of the altered sections appears to increase towards the base of the borehole.

The imprint of alteration makes it difficult to detect lithological changes. The heat production in the top 45 m (3 to 4 $\mu W/m^3$) is distinctly lower than at depth and more in line with values derived from surface samples from the Caldew outcrop (Webb & Brown 1984a). The change at about 45 m probably coincides with the top of the white granite as identified in the upper core. The slightly less evolved grey granite in the middle core (Webb & Brown 1984a) appears to be characterized by a slightly lower heat production and slightly higher calibrated density (Figure 3.10) but the imprint of alteration has affected both the geophysical logs and the laboratory determinations. The logs suggest that the contact between the two types of granite occurs at about 130 m but it is difficult to be certain.

The heat production log is less well constrained than at Shap but is still considered to give a reasonable estimate of the variations between the cored sections. The in-situ heat production of the white granite between depths of 45 and 130 m is about 4.4 $\mu W/m^3$ and that of the grey granite (below 130 m) is about 4$\mu W/m^3$. The calibrated density log is similarly less well constrained than at Shap. The log shows a gradual increase in in-situ density from about 2.58 Mg/m^3 in the upper part of the borehole to about 2.67 Mg/m^3 at the base.

The histograms and cross-plots (Figures 3.11 and 3.12 respectively) contrast with those from the mainly fresh Shap Granite and clearly show the imprint of alteration. The crossplots (in particular Figures 3.12 c, d and e) show a distinct alteration trend towards lower resistivity, lower sonic velocity and higher porosity in the altered sections. The most altered zones occur below a depth of 180 m. The plots of estimated heat production against calibrated density (Figure 3.12a) and resistivity (Figure 3.12b) show separate populations of points corresponding to the granite above a depth of 46 m. Figure 3.12b shows a clear trend towards lower heat production in the less resistive (i.e. most altered and/or jointed) sections within this zone. Similarly, in the bottom half of the borehole the altered zones have the lowest heat production (but over the most altered sections the severe caving may have affected the response of the logging equipment).

CHAPTER 4

GENERALIZED THREE-DIMENSIONAL GRAVITY INTERPRETATION OF THE LAKE DISTRICT BATHOLITH

4.1 INTRODUCTION

The interpretation described in this chapter was carried out during 1983-4 under the auspices of both the HDR and Lake District multidisciplinary projects (see Preface). The objective was to define the general 3-D form of the Lake District batholith, both in order to improve understanding of the deep structure of the region and provide a basis for subsequent heat flow modelling. Attention was focussed mainly on the Shap and Skiddaw granites on which the heat flow boreholes were sited (see previous chapter and Appendix 3). The modelling was based on the regional gravity data collected during 1981-2 but was carried out prior to the detailed surveys (see Chapter 2). The gravity map on which the modelling was based is shown in Figure 4.1. Likewise, the interpretation was based on geological information available prior to the recent re-mapping programme and on published density data supplemented by limited additional sampling (i.e. prior to the detailed analysis of density variations described in Chapter 5). The interpretation was published as an open file report (see Appendix 1) and as a paper in the Journal of the Geological Society (a copy of the latter is included in this thesis at Appendix 2 as supplementary paper S1).

4.2 ROCK DENSITIES

Reliable density values for the Shap and Skiddaw granites were determined from the core samples and geophysical logs from the heat flow boreholes described in the previous chapter. Density measurements

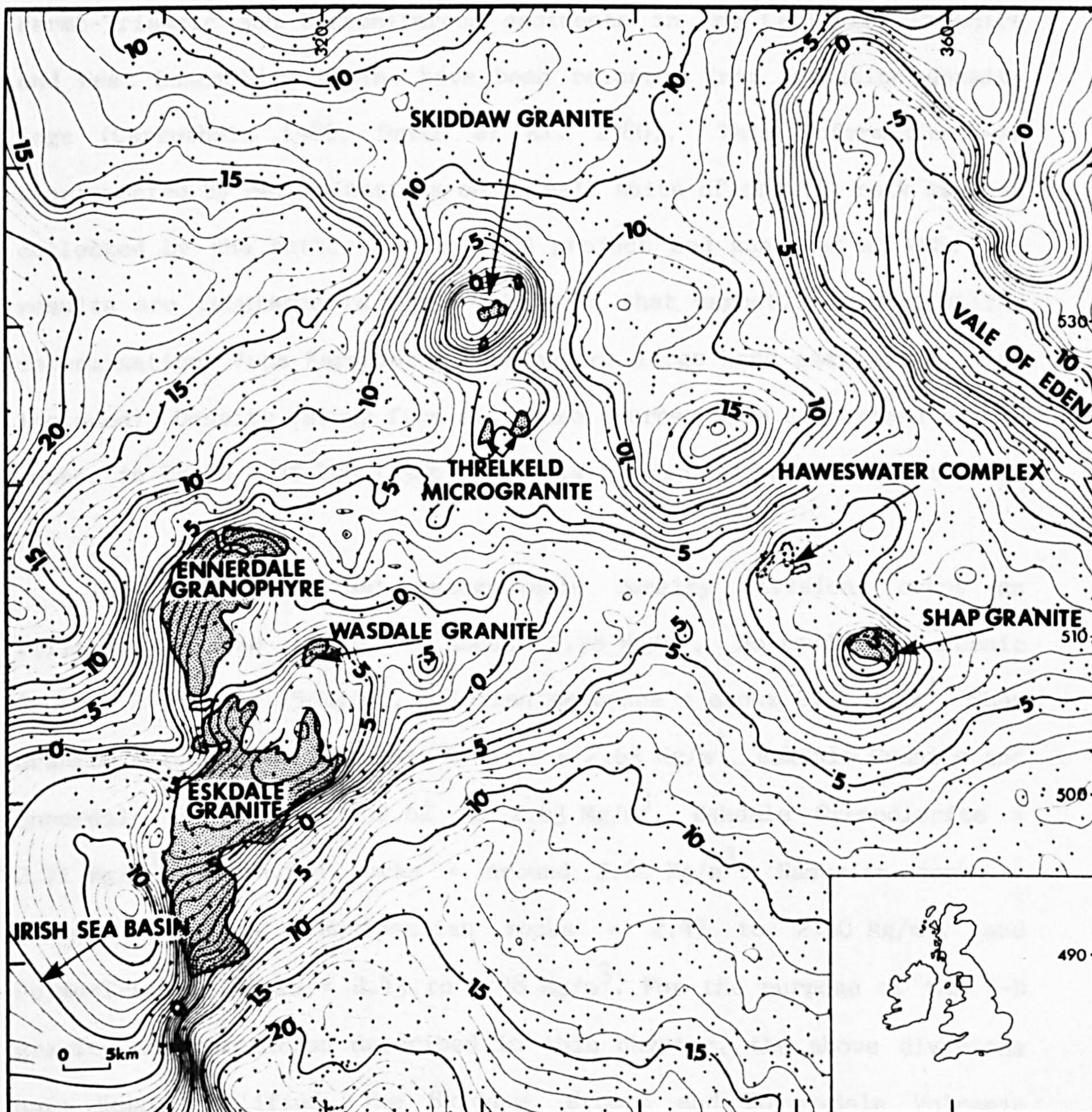


Figure 4.1 Bouguer gravity anomaly map of the Lake District used for the 3-D interpretation. Density for Bouguer corrections = 2.76 Mg/m^3. Dots indicate location of gravity observations.

on other Lower Palaeozoic, Carboniferous and Permo-Triassic rocks in the Lake District and northern England have been reported by Bott (1974) and Bott & Masson Smith (1957). Additional data relating to the Permo-Triassic and Carboniferous sediments in the Carlisle, Cheshire and West Lancashire basins have been reported from formation density logs (Carruthers 1980, Smith et al. 1980). This information was supplemented by determinations on a small suite of country rock samples collected by the author for the HDR project and analysed at BGS. The results are tabulated in Table 4.1 (note that magnetic susceptibility determinations from Kappameter readings on large hand samples are also included). Density values from all these sources were summarized by the author in Table 1 of Lee (1986) which is reproduced here as Table 4.2.

The data show that recognizable density divisions occur as follows: Skiddaw Group = about 2.78 Mg/m^3, Borrowdale Volcanic Group = 2.74 to 2.75 Mg/m^3, Silurian sequence = about 2.72 Mg/m^3, Shap Granite = 2.66 Mg/m^3, Skiddaw Granite = 2.63 Mg/m^3, Eskdale Granite and Ennerdale Granophyre = 2.62 to 2.63 Mg/m^3, Eskdale Granodiorite = 2.71 Mg/m^3, Dinantian rocks = around 2.60 Mg/m^3, Namurian rocks = around 2.53 Mg/m^3, Westphalian rocks = 2.47 to 2.60 Mg/m^3, and Permo-Traissic rocks = 2.43 to 2.48 Mg/m^3. For the purpose of the 3-D gravity interpretation described in this chapter, the above divisions have been simplified. The Skiddaw, Eycott and Borrowdale Volcanic groups have been taken together as a common 'geophysical basement' of density 2.76 Mg/m^3 and the principal density contrasts with respect to basement have been taken as follows:

(1) Shap Granite = -0.1 Mg/m^3

(2) Skiddaw, Eskdale, Ennerdale & concealed granite = -0.13 Mg/m^3

(3) Silurian sedimentary rocks = -0.04 Mg/m^3 (decreasing to

Table 4.1 Physical property determinations on a suite of samples collected to assist the 3-D gravity interpretation.

Formation	Sample number	NGR	Saturated density Mg m⁻³	Grain density Mg m⁻³	Porosity %	Magnetic susceptibility x10⁻³ SI	Description
Skiddaw Slates	ML 14	NY 337 266	2.79	2.83	2.0	<1	
	ML 18	NY 239 268	2.79	2.83	2.1	<1	
	ML 52	NY 362 306	2.80	2.82	1.2	<1	
	ML 54	NY 346 270	2.79	2.82	1.8	<1	
	ML 12	NY 342 324	2.78	2.79	0.7	<1	hornfels
	ML 13	NY 313 315	2.84	2.86	1.5	<1	hornfels
	ML 17	NY 312 301	2.79	2.83	2.2	<1	hornfels
Eycott Group	ML 50	NY 551 142	2.75	2.78	1.6	<1	
	ML 51	NY 548 144	2.78	2.80	1.2	<1	
	ML 53	NY 324 360	3.07	3.09	1.0	111	
Borrowdale Volcanic Group	ML 15	NY 303 205	2.84	2.84	0.4	<1	
	ML 16	NY 303 205	2.71	2.74	1.6	20	
	ML 31	NY 341 038	2.70	2.73	1.7	<1	
	ML 32	NY 353 035	2.69	2.71	1.4	<1	
	ML 33	NY 374 040	2.74	2.76	1.0	<1	
	ML 34	NY 400 076	2.75	2.78	1.8	<1	
	ML 35	NY 509 182	2.70	2.75	2.8	<1	
	ML 36	NY 509 183	2.71	2.75	2.1	<1	
	ML 37	NY 514 182	2.76	2.76	0.1	<1	
	ML 38	NY 505 156	2.76	2.76	0.0	19	
	ML 39	NY 480 132	2.71	2.72	0.5	<1	
	ML 40	NY 479 122	2.78	2.79	0.5	<1	
	ML 41	NY 476 111	2.72	2.73	0.6	<1	
	ML 42	NY 529 150	-	-	-	<1	
	ML 43	NY 565 105	2.87	2.87	0.2	<1	
	ML 55	NY 397 211	2.85	2.86	0.9	9.7	
	Mean of localities		2.75	2.77			
Coldwell Beds and Brathay Flags	ML 44	NY 560 078	2.72	2.73	0.5	3.6	
	ML 45	NY 556 076	2.74	2.75	0.3	3.1	
	ML 46	NY 553 074	2.67	2.69	1.0	<1	
	ML 47	NY 553 074	2.78	2.79	0.8	<1	
Coniston Grits	ML 29	SD 286 939	2.67	2.70	2.2	<1	
	ML 30	SD 286 939	2.71	2.74	1.6	<1	
Bannisdale Slates	ML 21	SD 474 953	2.64	2.71	4.0	<1	
	ML 22	SD 447 951	2.70	2.76	3.3	<1	
	ML 23	SD 409 944	2.72	2.76	2.0	<1	
	ML 24	SD 402 945	2.62	2.69	3.6	<1	
	ML 25	SD 385 897	2.69	2.75	3.1	<1	
	ML 26	SD 385 889	2.73	2.78	2.3	<1	
	ML 27	SD 362 858	2.69	2.74	2.8	<1	
	ML 28	SD 290 911	2.73	2.76	1.6	<1	
	ML 48	NY 555 055	2.69	2.70	0.4	<1	
	ML 49	NY 556 051	2.72	2.73	2.1	<1	
	Mean of localities		2.69*	2.74			
Skiddaw Granite	PW 100	NY 324 324	2.61	2.63	1.1	<1	weathered
	PW 105	NY 315 309	2.56	2.63	4.1	<1	weathered
	PW 106	NY 313 302	2.60	2.63	1.8	<1	weathered
	PW 107	NY 311 311	2.59	2.61	1.2	<1	fine grained
	PW 109	NY 314 313	2.60	2.62	1.7	<1	fine grained, weathered
	PW 110	NY 327 326	2.68	2.72	2.6	<1	greisened
	PW 111	NY 325 325	2.61	2.63	1.4	<1	fresh
Carrock Fell Complex	ML 10	NY 354 331	2.92	2.93	0.8	<1	gabbro
	ML 11	NY 356 326	2.84	2.85	0.7	<1	garbbro
	PW 103	NY 350 338	2.66	2.66	0.3	23	granophyre
Threlkeld Microgranite	PW 101	NY 329 243	2.66	2.67	0.9	<1	
	PW 102	NY 328 244	2.68	2.69	0.7	<1	
	PW 104	NY 321 221	2.70	2.71	0.3	<1	
Haweswater Complex	MN 2	NY 4942 1520	2.72	2.73	0.5		gabbro
	MN 128G	NY 5010 1670	2.80	2.83	1.8		gabbro (in area of dolerite)
	MN 206	NY 4958 1476	2.76	2.78	1.3		gabbro (in area of andesite)
	MN 98	NY 4941 1614	2.86	2.88	1.0		microdiorite
	MN 11	NY 4826 1517	2.77	2.83	3.1		dolerite
	MN 193	NY 5001 1419	2.72	2.74	1.3		dolerite
	MN 173	NY 4989 1483	2.70	2.72	0.7		dolerite
	MN 197	NY 5044 1421	2.73	2.75	1.4		dolerite
	MN 266	NY 4894 1630	2.77	2.79	1.3		dolerite
	MN 167	NY 4975 1472	2.73	2.74	0.8		dolerite

Notes

(1) Density and porosity determinations were carried out by the Engineering Geology Unit of BGS (Entwisle, 1983 and 1984).

(2) Magnetic susceptibility values were determined by MKL from Kappameter readings on large hand samples.

(3) Samples prefixed ML were collected by MKL. Samples prefexed PW were collected by Dr P. C. Webb (Open University), samples prefixed MN were collected by Dr M. J. C. Nutt (BGS).

(4) Samples prefixed ML and PW were split into 2 or 3 sub-samples for the density and porosity measurements. The values quoted in the table are the average of the measurements on the individual sub-samples.

* Data set includes samples with high 'porosity' due to split slates.

Table 4.2 Summary of density data for the Lake District region (Table 1 from Lee 1986).

Formation	Number of samples	Number of localities	Saturated density ($Mg\,m^{-3}$)	Source	Comments
Skiddaw Slates	53	4	2.77 ± 0.01	Bott 1978	
Skiddaw Slates	8	4	2.79 ± 0.01	Lee 1984*b*	Three additional samples of Skiddaw Slates converted to hornfels within the aureole of the Skiddaw Granite recorded densities of 2.78, 2.79 and 2.84 $Mg\,m^{-3}$
Borrowdale Volcanic Group	247	12	2.74 ± 0.04	Bott 1978	Mainly from the western half of the outcrop
Borrowdale Volcanic Group	30	14	2.75 ± 0.05	Lee 1984*b*	Mainly from the eastern half of the outcrop
Brathay Flags (Silurian)	41	2	2.74 ± 0.01	Bott 1978	
Bannisdale Slates (Silurian)	21	1	2.72 ± 0.01*	Bott 1978	
Kirby Moor Flags (Silurian)	20	1	2.69 ± 0.02*	Bott 1978	Grain density = 2.74 ± 0.01 (Bott 1974)
Bannisdale Slates and Coniston Grits (Silurian)	24	12	2.72 ± 0.03	Lee 1984*b*	Some of the slate samples were split resulting in an artificially high porosity. The value given is a theoretical saturated density calculated from the grain density assuming a porosity of 1%
Dinantian (Carboniferous Limestone)			2.60	Bott 1974	Calculated value for typical Yoredale sequence
Namurian (Millstone Grit)	logs	3	2.53	Smith *et al.* 1980	Representive *in situ* value from formation density logs in the Kirkham borehole and two boreholes in the Irish Sea
Westphalian (Coal Measures)	logs	3	2.60	Smith *et al.* 1980	From formation density logs as above but may not be typical (cf. a value of 2.47 $Mg\,m^{-3}$ reported by Bott & Masson Smith 1957)
Penrith Sandstone (Permian)	34	2	2.42 ± 0.02	Bott 1978	
St Bees Shale (Permian)	17	2	2.46 ± 0.01	Bott 1978	
St Bees Sandstone (Triassic)	57	5	2.22 ± 0.07	Bott 1978	
Permo-Triassic succession	logs	4	2.48	Smith *et al.* 1980	Representative *in situ* value from formation density logs in the Prees and Kirkham boreholes, and two boreholes in the Irish Sea
Permo-Triassic succession	log	1	2.45	Carruthers 1980	Representative *in situ* value from the formation density log in the lower 600 m of the Silloth borehole (St Bees Sandstone to the base of the Permo–Trias)
Permo-Triassic succession	log	1	2.43	Lee 1984*b*	Representative *in situ* value from the formation density log in an offshore borehole
Shap Granite	core and log	1	2.66	Lee 1984*a*	Representative value from the Shap heat flow borehole based on determinations on core samples and the calibrated formation density log

(*Contd.*)

Formation	Number of samples	Number of localities	Saturated density (Mg m^{-3})	Source	Comments
Skiddaw Granite	core and log	1	2.63	Lee 1984*a*	Representative value from the Skiddaw heat flow borehole based on core samples and the density log as at Shap. The granite is extensively altered throughout. The average *in situ* density in the upper half of the borehole is about 2.58 Mg m^{-3} and the density increases to about 2.66 Mg m^{-3} at the base
Eskdale Granite (muscovite granite)	44	7	2.62 ± 0.01	Bott 1978	
Eskdale Granite (southern biolite granodiorite)	15	2	2.71 ± 0.02	Bott 1978	
Ennerdale Granophyre	14	2	2.62 ± 0.01	Bott 1978	
Threlkeld Microgranite	17	1	2.67 ± 0.03*	Bott 1978	
Carrock Fell Gabbro	4	2	2.88 ± 0.06	Lee 1984*b*	
Haweswater Complex					
Gabbro	3	3	2.76 ± 0.04	Lee 1984*b*	
Microdiorite	1	1	2.86	Lee 1984*b*	
Dolerite	6	6	2.74 ± 0.03	Lee 1984*b*	

The standard deviation of localities is shown, except when marked by * where the standard deviation of the samples from the single locality is given.

$-0.03\ Mg/m^3$ at the base)

(4) Carboniferous sedimentary rocks = $-0.15 Mg/m^3$

(5) Permo-Triassic sedimentary rocks = $-0.30\ Mg/m^3$

Two points should be noted when considering the results of modelling based on these contrasts. Firstly, the Borrowdale Volcanic Group is characterized by a wide range of values but, on average, seems to be about $0.03\ Mg/m^3$ less dense than the Skiddaw Group. Density variations within the Eycott and Borrowdale Volcanic groups are not sufficiently well known for the effects of these groups to be modelled separately but the difference in average density between these and the Skiddaw Group should be borne in mind. Secondly, the restriction to only two densities for the granite batholith will limit the validity of subsequent models in areas where lateral density variations occur. The two-dimensional models of Bott (1974) included a number of lateral variations in what is obviously a composite batholith but these were not always supported by density measurements (see Chapter 5 for further discussion of density variations within the batholith and Lower Palaeozoic sequence based on more recent data).

In spite of these observations the density contrasts adopted are considered to be sufficently representative to give a satisfactory generalized model of the three-dimensional form of the Lake District batholith.

4.3 SEPARATION OF ANOMALIES

The negative gravity anomalies arising from the relatively low density Silurian, Carboniferous and Permo-Triassic sedimentary rocks interfere and overlap both with each other and with the anomalies associated with the granites. The entire suite of anomalies is superimposed on the general regional rise in the level of Bouguer anomaly towards the west. In order to interpret the three-dimensional shape of the granite batholith its anomaly must first be isolated by modelling and removing the effects of the surrounding formations and defining the trend of the background field across the region. The background field for the purpose of the present interpretation was taken to be the Bouguer anomaly distribution that would exist in the absence of all low density formations; that is if the basement rocks (Skiddaw, Borrowdale Volcanic and Eycott groups) reached the surface everywhere and there were no low density granitic intrusions. The background is particularly difficult to define in the eastern part of the area where the effects of Silurian, Carboniferous and Permo-Triassic sedimentary rocks overlap and where the adjacent Weardale and Wensleydale granites also affect the Bouguer anomaly level.

A suite of computer programs based on the method of Talwani and Ewing (1960) was used to calculate and remove the effects of the low density structures surrounding the Lake District batholith (unpublished BGS software, J.C. Tombs). The three-dimensional form of each structure was defined in terms of polygonal depth contours from the available geological control (BGS memoirs, maps, boreholes and publications, see below). The gravity effect of each model was calculated on a 1 km square grid over the (70 x 70 km) area shown in Figure 4.1. In practice it was necessary to set up trial models which were then adjusted in areas of poor geological control until a satisfactory fit was obtained. This proceedure is subjective but is considered to be sufficiently accurate for the purpose of removing the broad-scale effects of the surrounding structures. A model was deemed to be satisfactory when the effects of the structure it represents had broadly disappeared from the reduced anomaly map (i.e. the observed field minus the calculated field). No attempt was made to interpret small scale anomalies over the sedimentary sequences in detail.

Figure 4.2 shows the model used for the Permo-Triassic sequence. In addition to the appropriate BGS maps and memoirs, the part of the model covering the Vale of Eden takes account of gravity interpretations by Bott (1974) and Collar (1981). The structure of the Carlisle Basin takes account of the Silloth borehole just to the north of the area [NY 3123 5548] which penetrated 1312 m of Permo-Triassic rocks resting unconformably on Lower Carboniferous strata. The model also takes account of seismic and magnetic data in the Carlisle Basin reviewed by Carruthers (1980). The thickness of the Permo-Triassic rocks on the western side of the Lake District is taken from a supplementary map published with the 1:50,000 series Geological map covering sheets 37 and 47 (Gosforth and Bootle). The map shows that the sequence thickens rapidly to reach 1000 m in the Seascale, Drigg and Bootle areas just to the west of the Eskdale Granite. The model assumes that the Permo-Triassic rocks continue to thicken to 3 km offshore into the Irish Sea Basin (Colter & Barr 1975).

Figure 4.3 shows generalized models of the depth to the base of the Carboniferous and Silurian rocks. The model for the Carboniferous is somewhat conjectural, particularly where the sediments lie concealed beneath the later Permo-Triassic sequence. The depth to the base of the Carboniferous has been set at 2 km in the Vale of Eden which is closer to the estimate given by Bott (1974) than that of over 3 km given by

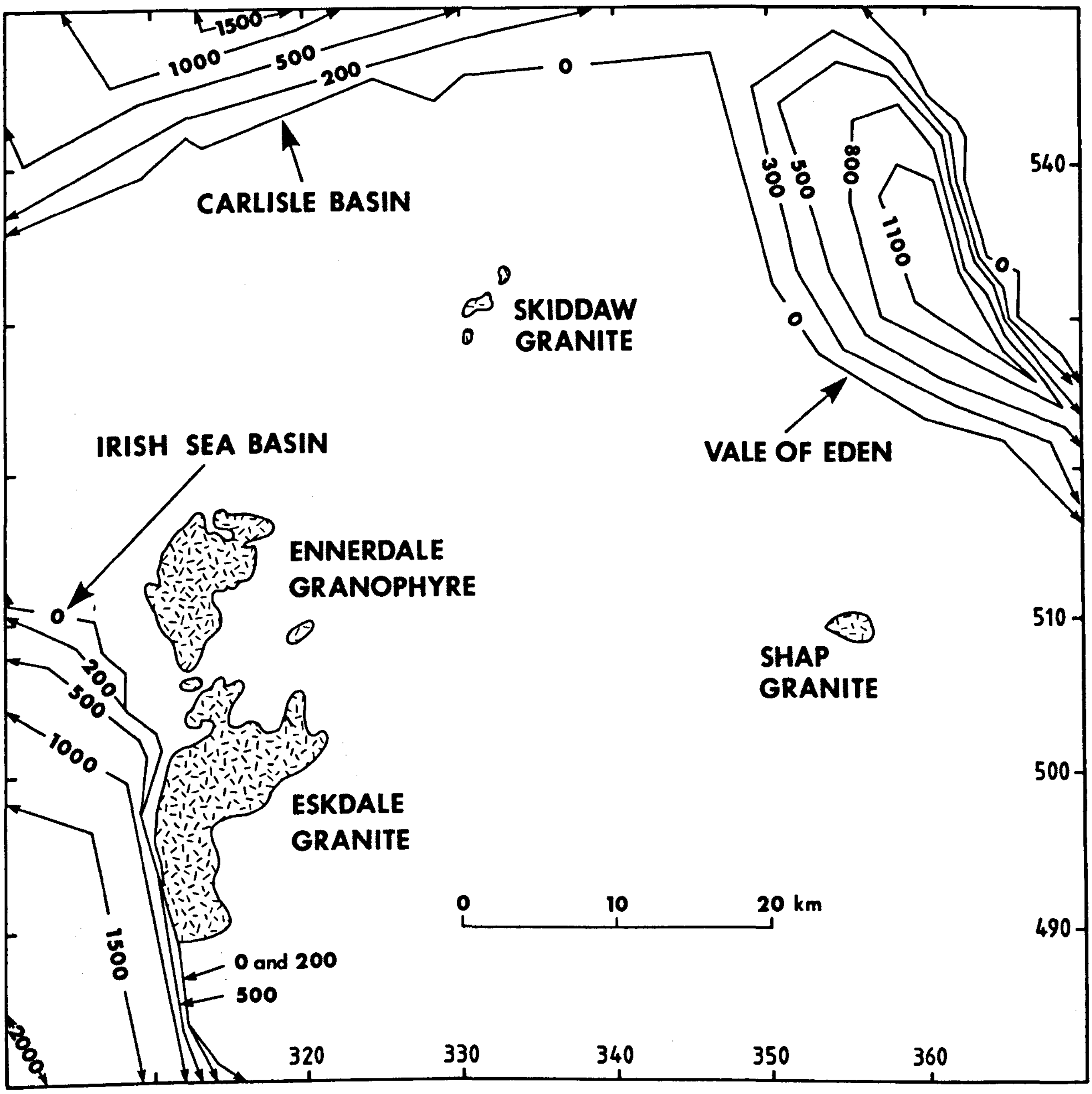


Figure 4.2 Simplified model of depth to base of Permo-Triassic sedimentary rocks used to calculate their gravity effect. Contours in metres. Density contrast = -0.03 Mg/m^3 with respect to basement of density 2.76 Mg/m^3.

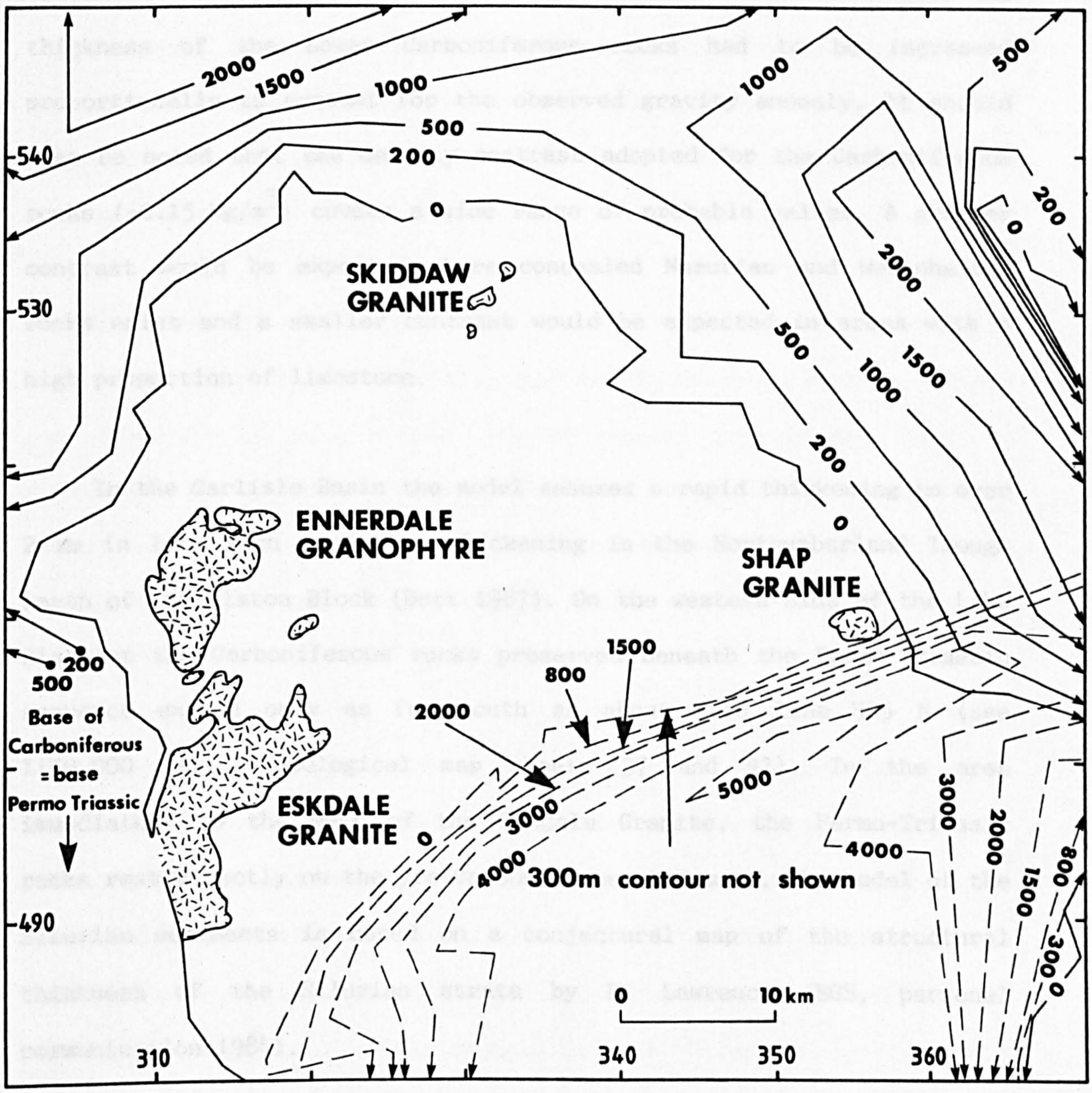


Figure 4.3 Model of depth to base of Carboniferous (solid lines) and Silurian (dashed lines) sedimentary rocks used to calculate their gravity effect. Contours in metres. Density contrast of Carboniferous rocks = -0.15 Mg/m^3. Density contrast of Silurian rocks = -0.04 Mg/m^3 (contours 0, 300, 800 1500, 2000 and 3000 m) and -0.03 Mg/m^3 (contours 4000 and 5000 m), all with respect to basement of density 2.76 Mg/m^3.

Collar (1981). It should be noted, however, that Collar's interpretation assumed a density contrast of only $-0.05\ Mg/m^3$ between the Lower Carboniferous rocks and the basement which meant that the thickness of the Lower Carboniferous rocks had to be increased proportionally to account for the observed gravity anomaly. It should also be noted that the density contrast adopted for the Carboniferous rocks ($-0.15\ Mg/m^3$) covers a wide range of probable values. A greater contrast would be expected where concealed Namurian and Westphalian rocks exist and a smaller contrast would be expected in areas with a high proportion of limestone.

In the Carlisle Basin the model assumes a rapid thickening to over 2 km in line with a similar thickening in the Northumberland Trough north of the Alston Block (Bott 1967). On the western side of the Lake District the Carboniferous rocks preserved beneath the Permo-Triassic sequence extend only as far south as about grid line 505 N (see 1:50,000 series Geological map sheets 37 and 47). In the area immediately to the west of the Eskdale Granite, the Permo-Triassic rocks rest directly on the pre-Carboniferous basement. The model of the Silurian sediments is based on a conjectural map of the structural thickness of the Silurian strata by D. Lawrence (BGS, personal communication 1984).

The Criffel, Weardale and Wensleydale granites lie entirely outside the area shown in Figure 4.1. However, these are all large, deep-seated, low density bodies and it was deemed necessary to estimate their gravity effect on the field across the Lake District. Simple three-dimensional models (not shown) were defined, based on previous two-dimensional interpretations by Bott (1967), Wilson & Cornwell

(1982) and Bott & Masson Smith (1960) for the Weardale, Wensleydale and Criffel granites respectively. The model for the Weardale Granite was confined to the Alston Block and did not include the postulated buried ridge beneath the Vale of Eden. No attempt was made to achieve an exact fit to the Bouguer anomaly pattern over the granites themselves. The computed gravity field due to the combined effect of all three adjacent granites is shown in Figure 4.4.

The combined effect of all the low density structures is shown in Figure 4.5. This field was subtracted from the observed Bouguer anomaly map (Figure 4.1) to give the reduced Bouguer anomaly map shown in Figure 4.6 The reduced map represents the Bouguer anomaly values which would be observed if the Permo-Triassic, Carboniferous and Silurian sequences, and the surrounding granite bodies were replaced by basement rocks of density 2.76 Mg/m^3.

By comparing Figure 4.6 with the observed Bouguer anomaly map shown in Figure 4.1 it can be seen that the effects of the surrounding formations have been largely removed. However, the gravity field on the western edge of the Alston Block, around the Cross Fell inlier, has not been fully accounted for and minor anomalies remain on the western coastal strip adjacent to the Eskdale Granite. Reference to Figure 4.1 shows that in both these areas the gravity observations are rather widely spaced and the Bouguer anomalies are poorly defined. In the case of the western coastal strip additional offshore observations are required adequately to define the field.

The most striking remaining anomaly not clearly associated with the Lake District granites is the roughly WNW trending anomaly on the

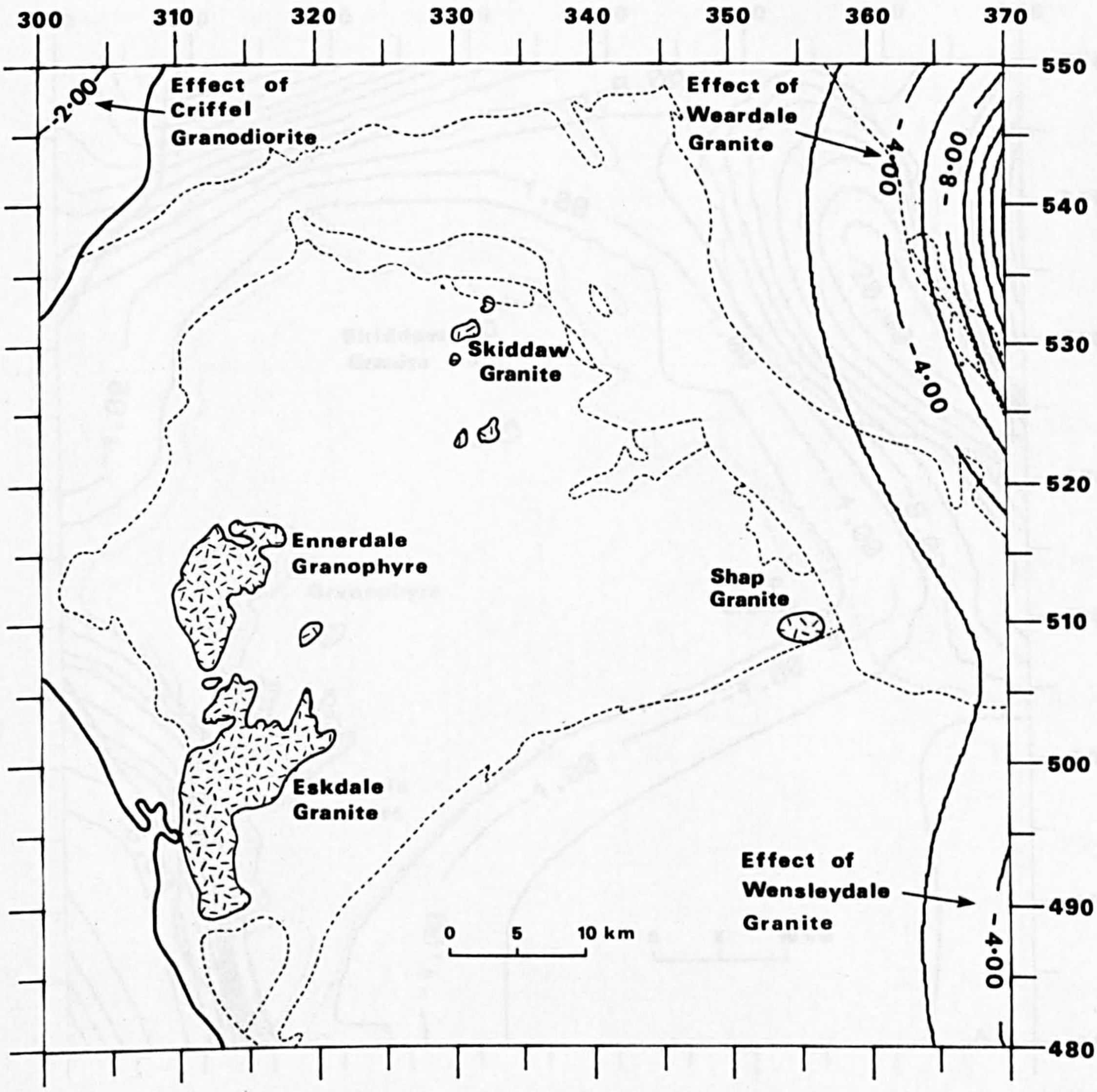


Figure 4.4 Bouguer anomaly due to adjacent Weardale, Wensleydale and Criffel granites. Anomalies calculated on a 1 km grid from 3-D models of the granites outside the margins of the map. Computer-drawn contours at 2 mGal intervals.

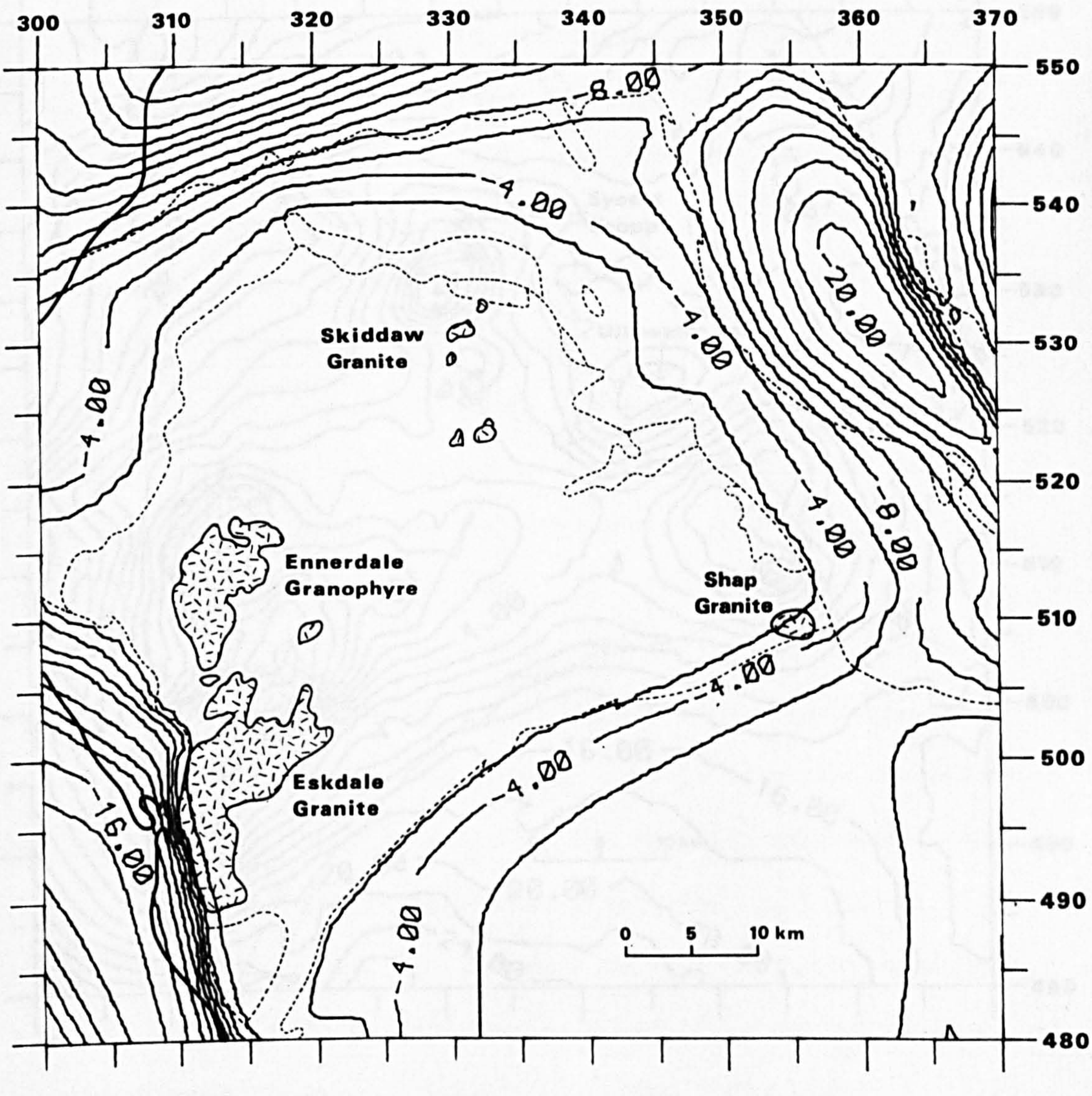


Figure 4.5 Gravity anomaly due to the effects of all low density rocks surrounding the Lake District (i.e Permo-Triassic, Carboniferous and Silurian sedimentary rocks and adjacent Weardale, Wensleydale and Criffel granites). The anomalies due to the sedimentary sequences were calculated on a 1 km grid from the models shown in Figures 4.2 and 4.3.

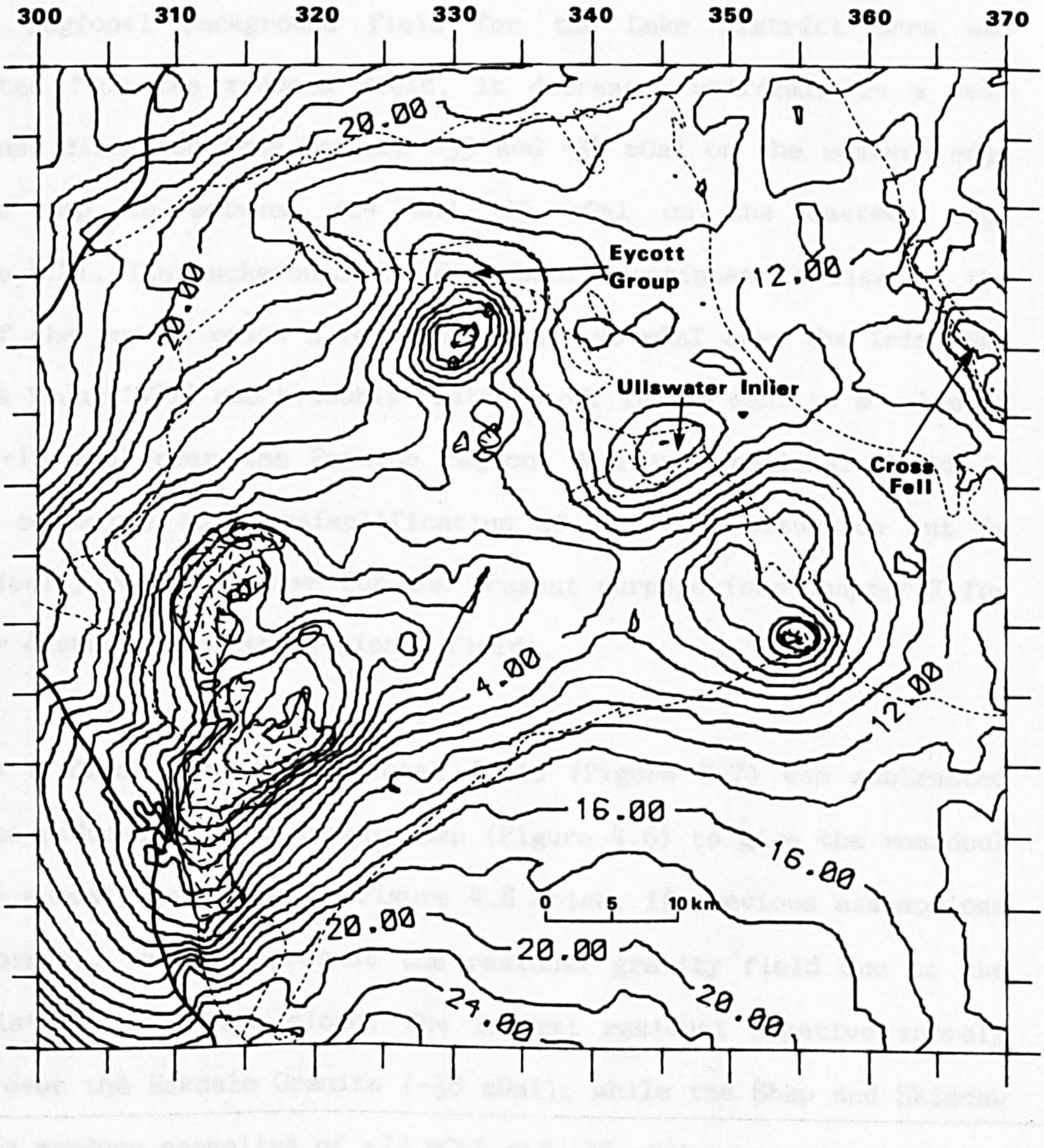


Figure 4.6 Reduced Bouguer gravity anomaly map (i.e. observed field minus the effects of all surrounding low density rocks). Calculated by subtracting the field shown in Figure 4.5 from the observed Bouguer anomaly on a 1 km grid.

northern margin of the Skiddaw Group. Closer inspection of the observed field suggests that this might be due to low density rocks within, or associated with, the Eycott Volcanic Group (this anomaly is considered in more detail in Chapter 7).

A regional background field for the Lake District area was estimated from the reduced field, it decreases uniformly in a near west-east direction from between +33 and +34 mGal on the western edge of the map to between +14 and +15 mGal on the eastern edge (Figure 4.7). The background field probably continues to rise to the west of the map to reach a value of about +40 mGal over the Irish Sea (Bott & Young 1971) and probably flattens off in the east to a value of about +10 mGal over the Pennine region. A linear regional field is almost certainly an oversimplification of the true situation but is sufficiently representative for the present purpose (see Chapter 7 for further discussion of the regional field).

As a final step the regional field (Figure 4.7) was subtracted from the reduced Bouguer anomaly map (Figure 4.6) to give the residual gravity anomaly map shown in Figure 4.8 which, if previous assumptions were correct, should represent the residual gravity field due to the Lake District batholith alone. The largest residual negative anomaly occurs over the Eskdale Granite (-38 mGal), while the Shap and Skiddaw granites produce anomalies of -22 mGal and -28 mGal respectively.

4.4 COMPUTATION OF THE BATHOLITH MODEL

The residual gravity field due to the Lake District batholith (Figure 4.8) was interpreted using a three-dimensional inversion program by Tombs (1976) modified by the present author to cover a

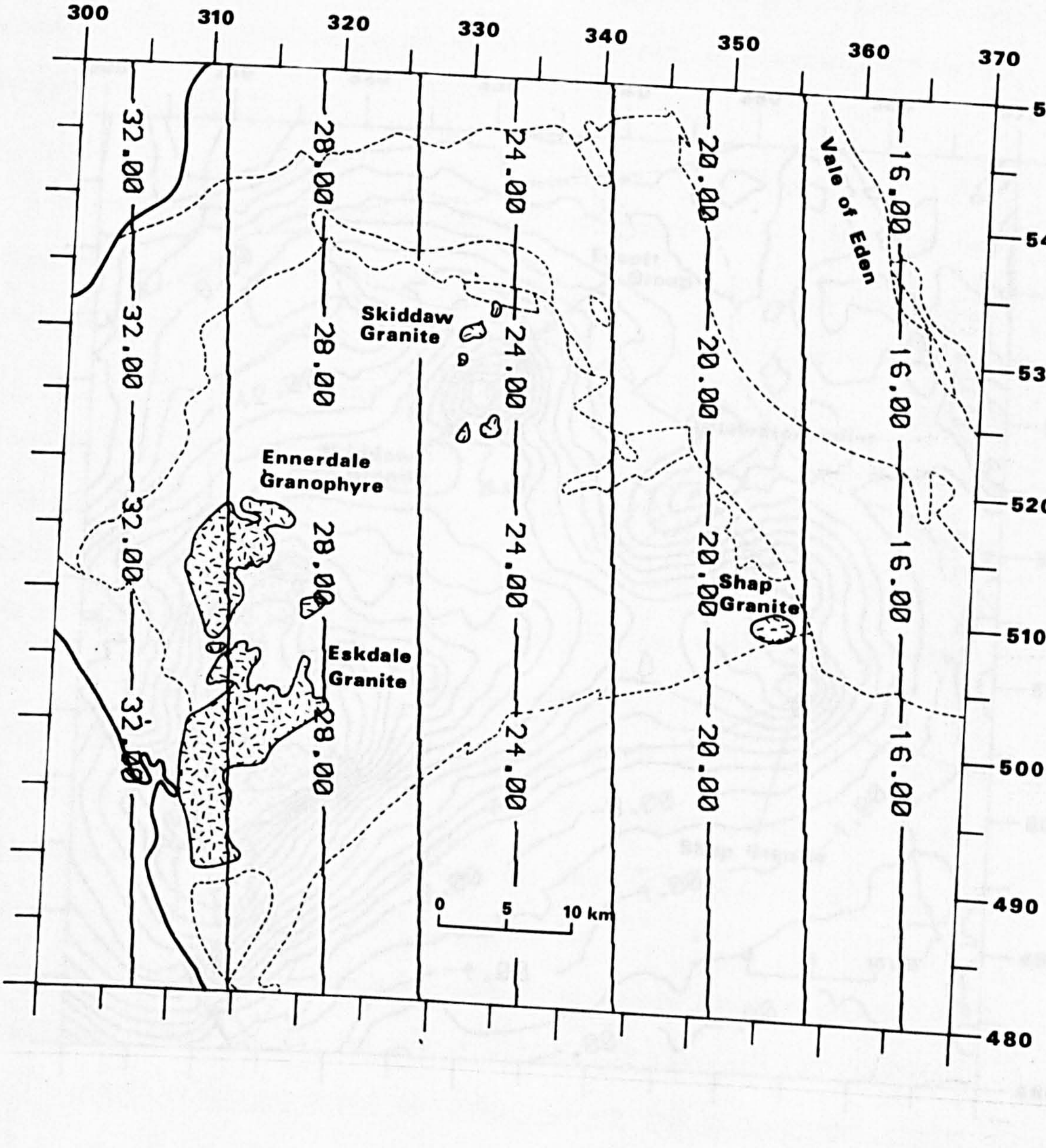


Figure 4.7 Estimated regional gravity field.

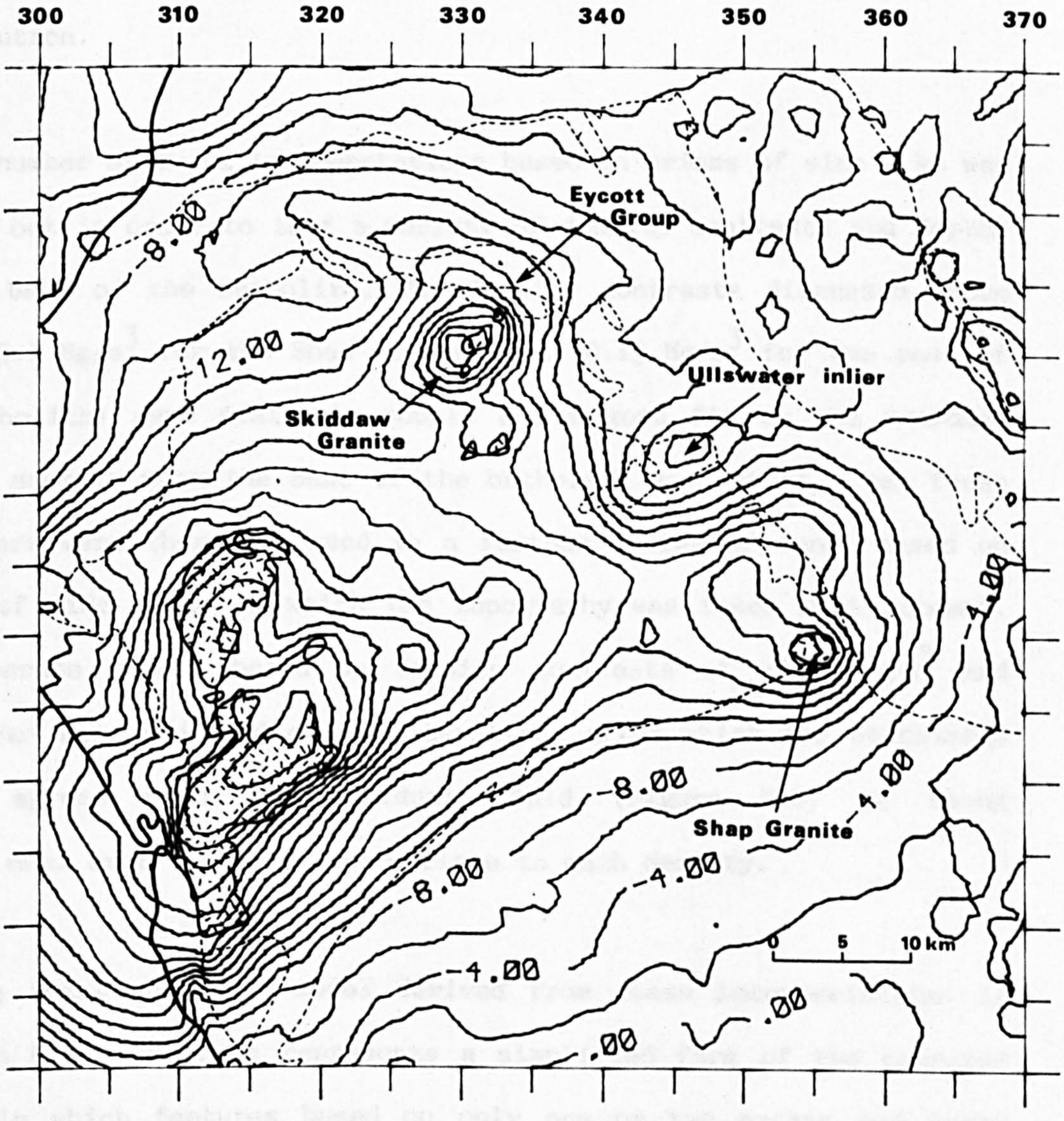


Figure 4.8 Residual gravity anomaly due to the Lake District batholith (and other low density rocks not previously taken into account). Generated by subtracting the regional field (Figure 4.7) and the effects of surrounding low-density formations (Figure 4.5) from the observed Bouguer anomaly (Figure 4.1).

larger area. The program calculates the theoretical field due to a three-dimensional model consisting of vertical square prisms and then iteratively adjusts the top of the model until a good fit with the 'observed' anomaly is obtained. The program does not allow for complex density variations within the model but gives a good generalized outline of the subsurface shape of a body based on simplified density distribution.

A number of trial interpretations based on prisms of side 2 km was carried out in order to test a variety of density contrasts and depths to the base of the batholith. The density contrasts discussed above (i.e. -0.1 Mg/m^3 for the Shap Granite and -0.13 Mg/m^3 for the rest of the batholith) gave realistic models and a good fit to the residual gravity anomaly when the base of the batholith was set at 9 km. These parameters were therefore used in a further series of runs, based on prisms of side 1 km, in which the topography was taken into account. Two separate models based on density contrasts of -0.13 Mg/m^3 and -0.1 Mg/m^3 were adjusted over 8 iterations after which the calculated fields agreed with the residual field (Figure 4.8) to about +/- 0.5 mGal over the areas appropriate to each density.

The final composite model derived from these interpretations is shown in Figure 4.9. It represents a simplified form of the computer output in which features based on only one or two prisms and those obviously associated with non-granite anomalies (i.e. anomalies due to sedimentary rocks not completely removed by the previous modelling) have been ignored. Bearing in mind the simplified density distribution assumed in the interpretation, the model is considered to give a reasonable 'generalized' approximation to the three-dimensional form of

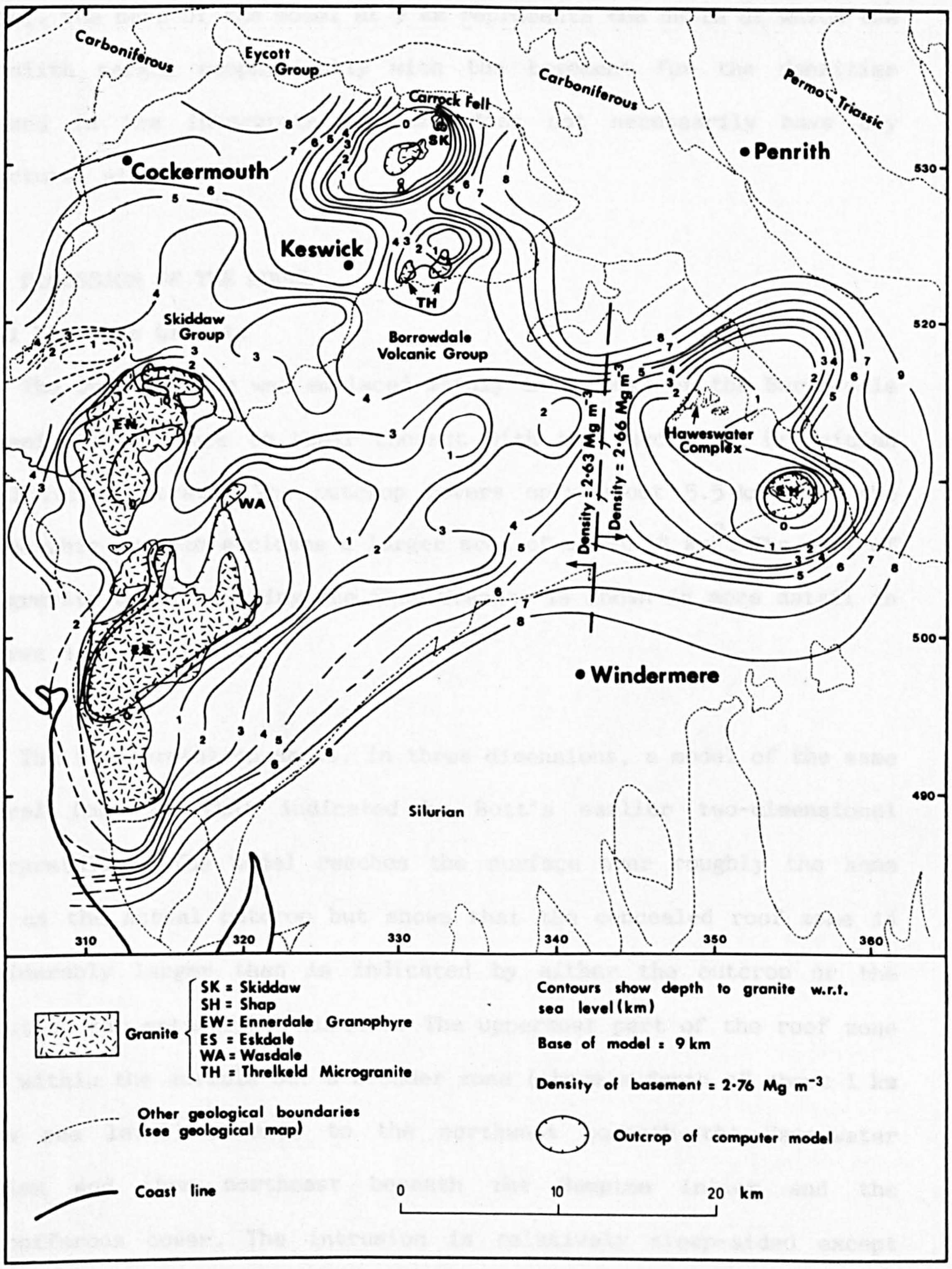


Figure 4.9 Generalized three-dimensional model of the Lake District granite batholith based on density values of 2.66 Mg/m^3 for the area around the Shap Granite and 2.63 Mg/m^3 for the rest of the batholith. Density of the 'basement' = 2.76 Mg/m^3. Contours show depth to granite roof in km below sea level. Base of model = 9 km.

the Lake District batholith (however, see qualifications dicussed below). The base of the model at 9 km represents the depth at which the batholith merges geophysically with the basement for the densities assumed in the interpretation, and does not necessarily have any structural significance.

4.5 DICUSSION OF THE MODEL

4.5.1 The Shap Granite

The Shap Granite was emplaced mainly into rocks of the Borrowdale Volcanic Group close to their contact with the succeeding Ordovician and Silurian strata. The outcrop covers only about 5.5 km^2 but the metamorphic aureole encloses a larger area of about 14 km^2. The part of the gravity model covering the Shap Granite is shown in more detail in Figures 4.10 and 4.11.

The interpretation shows, in three dimensions, a model of the same general form as that indicated by Bott's earlier two-dimensional interpretation. The model reaches the surface over roughly the same area as the actual outcrop but shows that the concealed roof zone is considerably larger than is indicated by either the outcrop or the extent of the metamorphic aureole. The uppermost part of the roof zone lies within the aureole but a broader zone (above a depth of about 1 km below sea level) extends to the northwest beneath the Haweswater Complex and then northeast beneath the Bampton inlier and the Carboniferous cover. The intrusion is relatively steep-sided except where it merges with the rest of the batholith.

The Haweswater Complex consists mainly of dolerite and is considered to be the site of a major eruptive centre of the Borrowdale

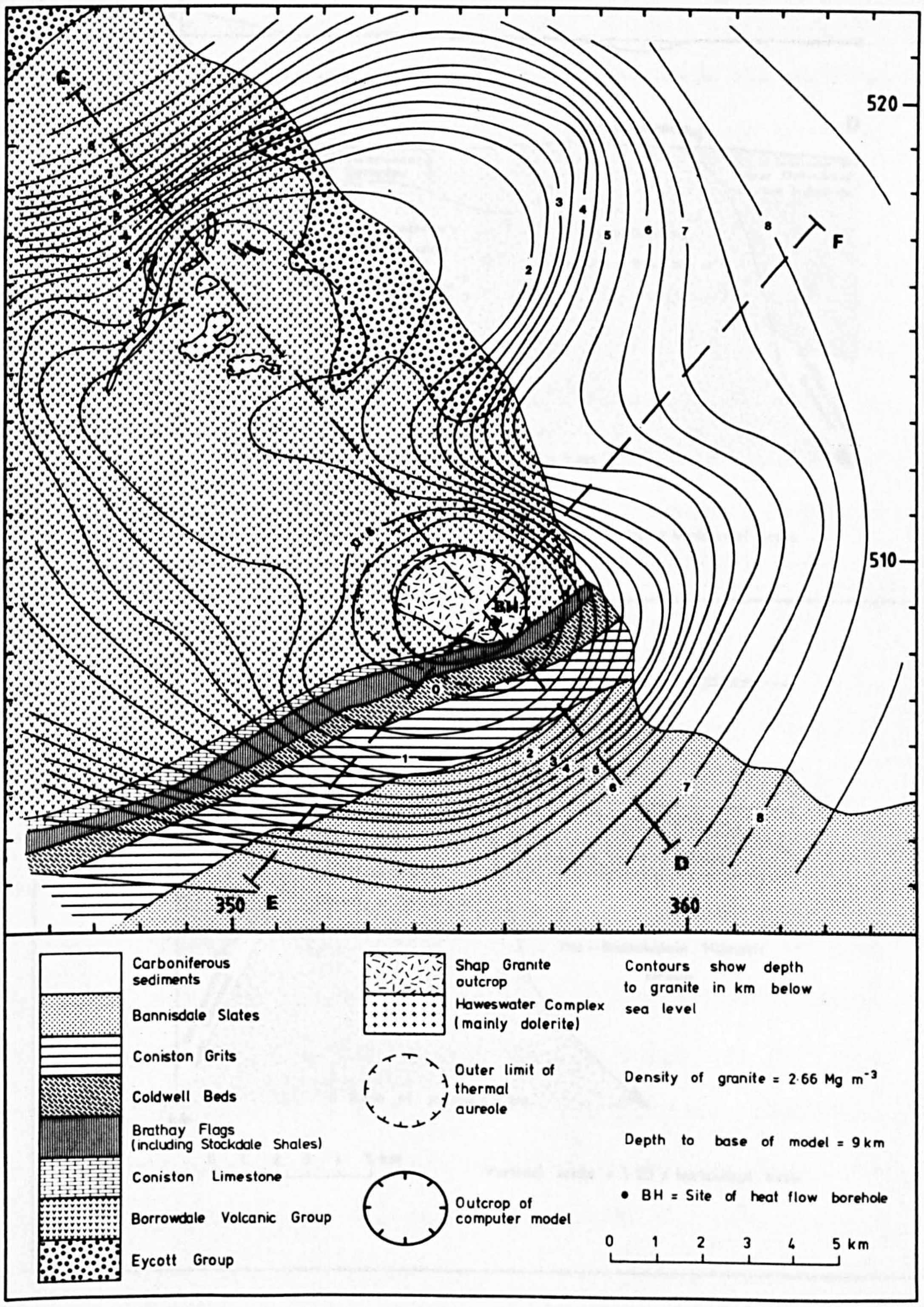


Figure 4.10 Three-dimensional model of the Shap Granite. Contour interval = 500 m. Sections CD and EF are shown in Figure 4.11.

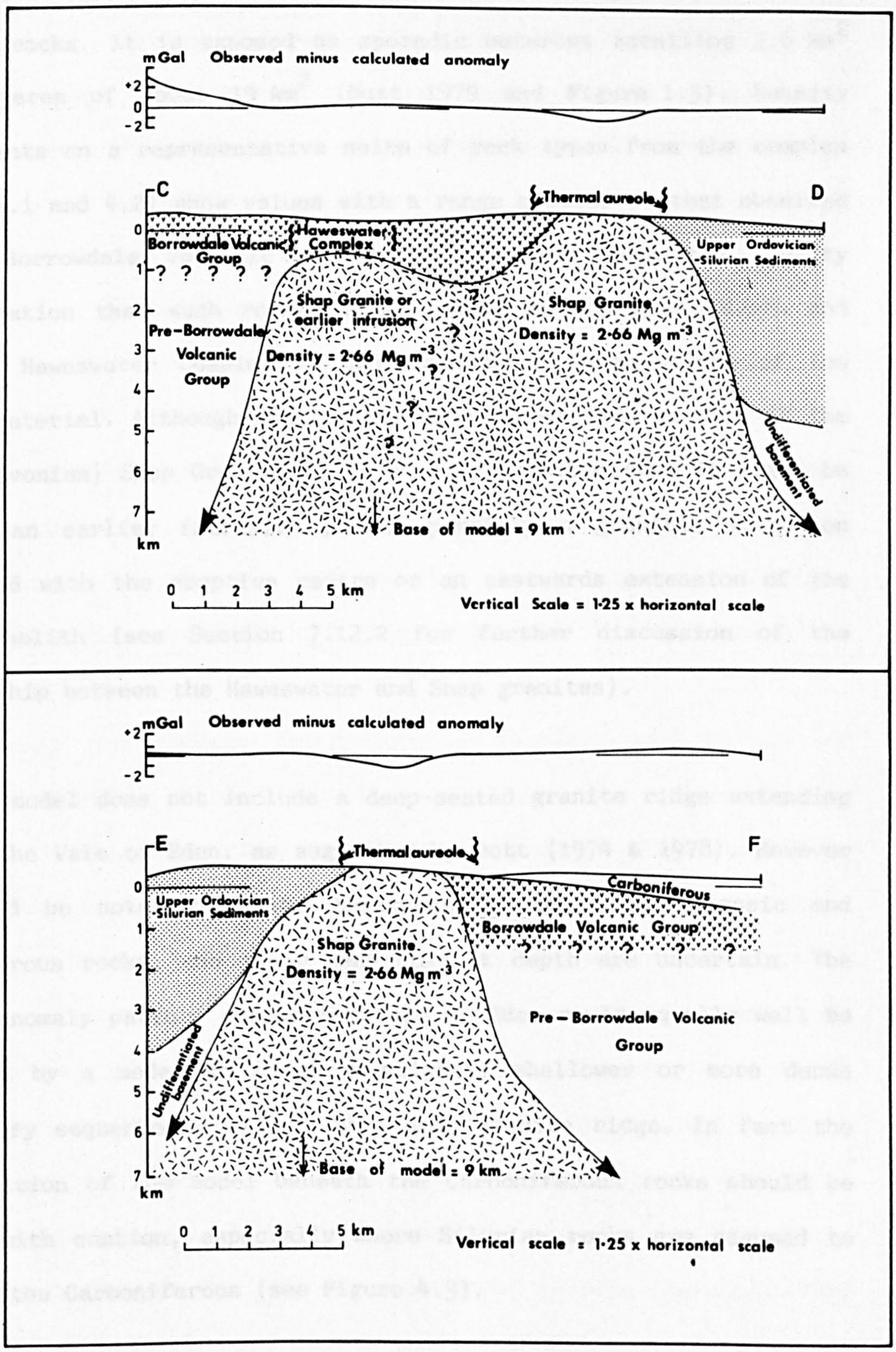


Figure 4.11 Sections CD and EF across the Shap Granite. The topographic profiles were derived from the gridded elevations of the gravity stations.

volcanic rocks. It is exposed as sporadic outcrops totalling 2.6 km^2 over an area of about 19 km^2 (Nutt 1979 and Figure 1.3). Density measurements on a representative suite of rock types from the complex (Tables 4.1 and 4.2) show values with a range similar to that observed in the Borrowdale Volcanic Group. It is clear from the gravity interpretation that such rocks cannot extend to any great depth and that the Haweswater Complex is underlain by a large volume of low density material. Although the gravity model shows this as part of the (early Devonian) Shap Granite it is equally possible that it might be part of an earlier intrusive phase; possibly a granitic intrusion associated with the eruptive centre or an eastwards extension of the main batholith (see Section 7.12.2 for further discussion of the relationship between the Haweswater and Shap granites).

The model does not include a deep-seated granite ridge extending beneath the Vale of Eden, as suggested by Bott (1974 & 1978). However it should be noted that the thickness of the Permo-Triassic and Carboniferous rocks, and their densities at depth are uncertain. The Bouguer anomaly pattern across the Vale of Eden could equally well be satisfied by a model in which a slightly shallower or more dense sedimentary sequence is offset by a deep granite ridge. In fact the whole section of the model beneath the Carboniferous rocks should be treated with caution, especially where Silurian rocks are assumed to underlie the Carboniferous (see Figure 4.3).

Bott's (1974) two-dimensional interpretation included a zone of lower density granite (2.63 Mg/m^3) immediately to the southeast of the Shap outcrop. The present three-dimensional interpretation shows that the anomaly can be modelled satisfactorily in terms of a granite of uniform density. The profiles across the model (Figure 4.11) show that the fit between the observed (residual) and computed anomalies is generally good. The mismatch of about 1 mGal over the centre of the granite outcrop can easily be accounted for by a small change in either the density contrast, background field or depth to base of the model. The mismatch of nearly 3 mGal at the northwestern end of section CD is more serious. The negative gravity anomaly over the Shap Granite is bounded on the northwest by a closed relative positive anomaly which remains even after removal of the regional field (see Figures 4.1 and 4.8). The positive anomaly occurs over the Ullswater inlier of the Skiddaw Group and might be due to high density rocks within the basement (see Chapters 7 and 8 for further discussion of this point).

Overall, the gravity interpretation suggests that granite of density 2.66 Mg/m^3 observed in the Shap heat flow borehole (see Chapter 3) extends to considerable depth. Granite of this density is characterized by a heat production of over 5 $\mu W/m^3$ in the borehole. From the geothermal viewpoint, the model offers no evidence for the widespread presence of a significantly denser, less evolved (and therefore less radiothermal) granite at depth. However it shoud be noted that the more basic and less radiothermal 'grey' granite observed in the middle core section has a density of 2.68 Mg/m^3 (Section 3.4) which is only slightly higher than the density of the normal 'pink' granite. The proportion of 'grey' granite could therefore increase significantly with depth without noticeably affecting the gravity anomaly.

The heat flow borehole is seen to be well within the roof zone and away from the edges of the intrusion (Figure 4.10). The high level roof zone (i.e. the part above sea level) covers an area of 13 km^2 while the broader roof zone (above a depth of about 1 km below sea level) covers an area of about 57 km^2. The total volume of the model east of grid line 345 E (down to a depth of 9 km) is about 1600 km^3 but this includes the part beneath the Haweswater Complex which, as explained above, may not be related to the Shap Granite proper.

4.5.2 The Skiddaw Granite

The Skiddaw Granite was emplaced into Skiddaw Group rocks close to the contact with the Eycott Volcanic Group. The granite is exposed in only three small outcrops but the extent of the metamorphic aureole suggests that it cuts across the older Carrock Fell Complex to the north (Eastwood et al.1968). The part of the gravity model covering the Skiddaw Granite is shown in more detail in Figures 4.12 and 4.13.

The interpretation shows, in greater resolution, a model of the same general form as that given by Bott (1974). The granite is a relatively flat-topped, steep-sided intrusion elongated in a NE-SW direction. The shape of the roof zone as defined by the gravity model corresponds well with the mapped thermal aureole and encompasses the three outcrops. The model reaches the surface over a slightly larger area than the Caldew outcrop, in the centre of the roof zone, and also in a small area on the southern margin of the Grainsgill outcrop. The model just fails to reach the surface beneath the small Sinnen Gill outcrop. The fit between the observed (residual) and calculated anomalies along section GH is generally better than 1 mGal. The small mismatch across part of the roof zone arises because the decrease in density in the uppermost part of the intrusion (see borehole logs in Section 3.5) has not been included in the model.

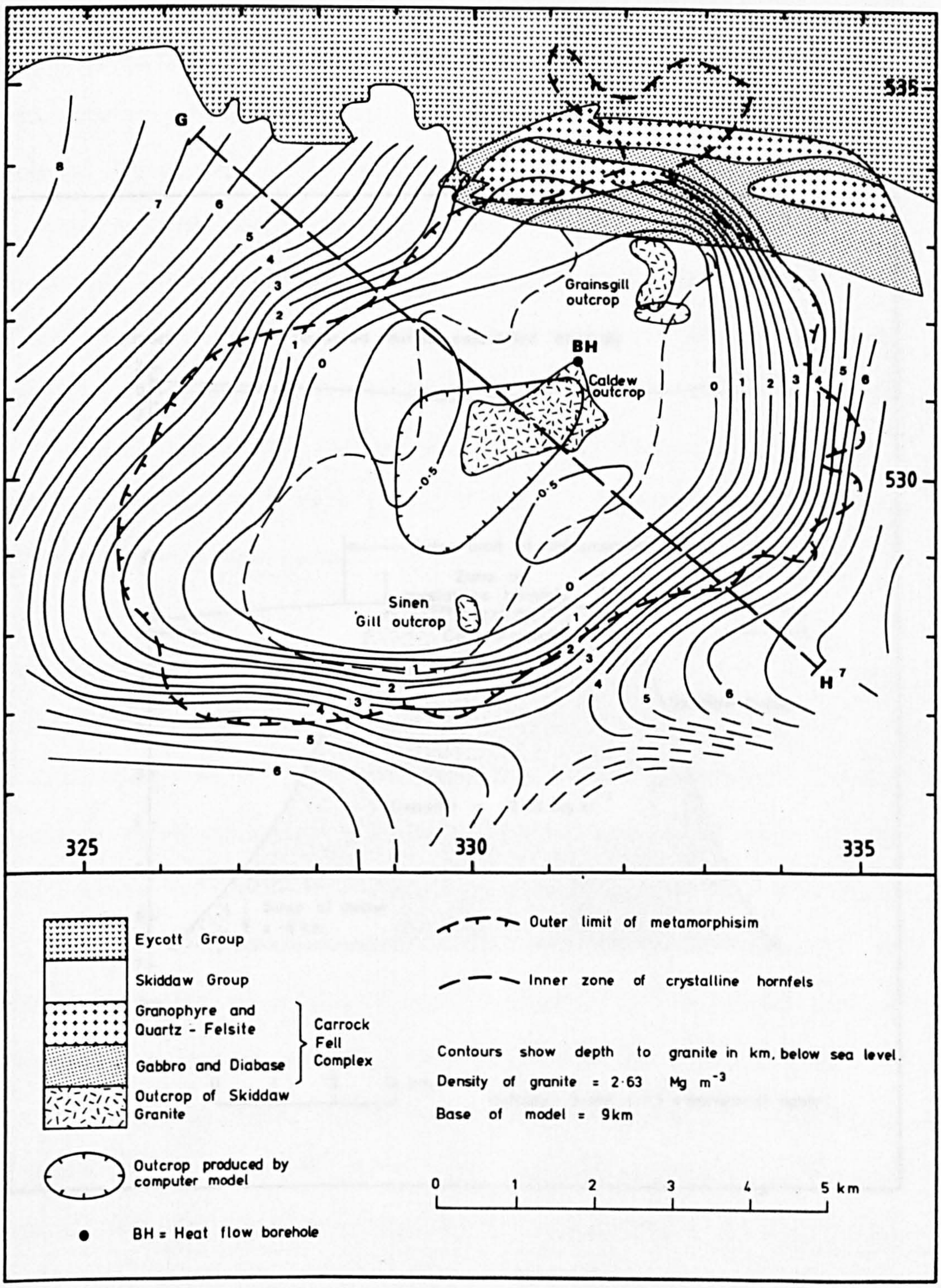


Figure 4.12 Three-dimensional model of the Skiddaw Granite. Contour interval = 500 m. Section GH is shown in Figure 4.13.

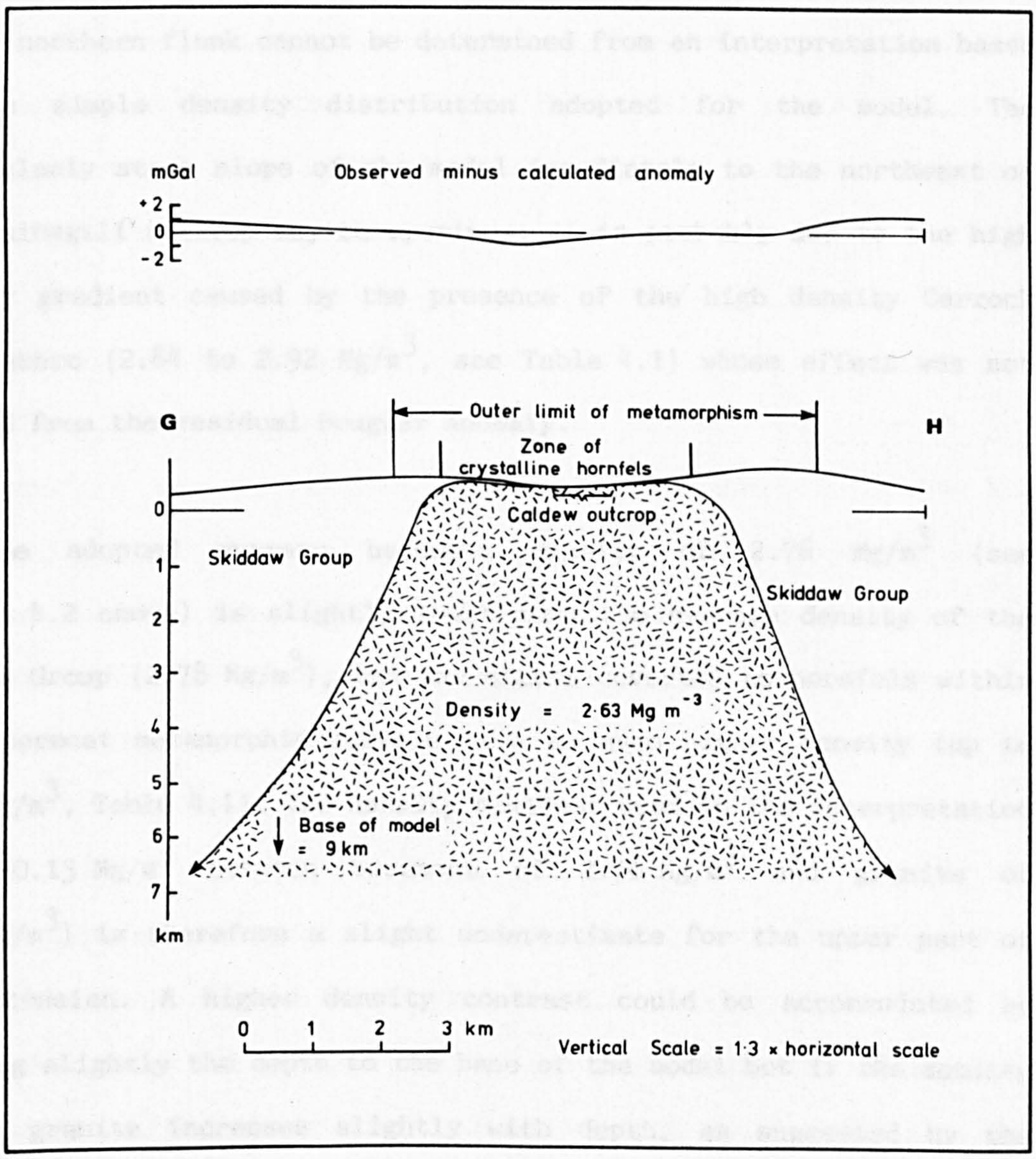


Figure 4.13 Section GH across the Skiddaw Granite. The topographic profile was derived from the gridded elevations of the gravity stations.

The model is not well constrained on the northern flank where the anomaly associated with the Eycott Volcanic Group interferes with that due to the granite (see Section 4.3 above). The granite clearly cuts across the Carrock Fell Complex and extends beneath the Eycott lavas as indicated by the shape of the metamorphic aureole, but the exact form of the northern flank cannot be determined from an interpretation based on the simple density distribution adopted for the model. The particularly steep slope of the model immediately to the northeast of the Grainsgill outcrop may be spurious; it is probably due to the high anomaly gradient caused by the presence of the high density Carrock Fell Gabbro (2.84 to 2.92 Mg/m^3, see Table 4.1) whose effect was not removed from the residual Bouguer anomaly.

The adopted average basement density of 2.76 Mg/m^3 (see Section 4.2 above) is slightly lower than the average density of the Skiddaw Group (2.78 Mg/m^3), and the slates coverted to hornfels within the innermost metamorphic aureole have an even higher density (up to 2.84 Mg/m^3, Table 4.1). The density contrast used in the interpretation (i.e -0.13 Mg/m^3 between basement of 2.76 Mg/m^3 and granite of 2.63 Mg/m^3) is therefore a slight underestimate for the upper part of the intrusion. A higher density contrast could be accommodated by reducing slightly the depth to the base of the model but if the density of the granite increases slightly with depth, as suggested by the density measurements on core samples and the geophysical logs (see Chapter 3), this would not be necessary. The general form of the model as depicted in Figure 4.12 would remain substantially unchanged within the range of possible density contrasts.

Overall, the gravity interpretation suggests that granite of relatively low density (around 2.63 Mg/m^3), extends to considerable depth (approximately 9 km). Granite of this density in the heat flow borehole is characterized by a heat production of over 4 $\mu W/m^3$ (see Section 3.5). From the geothermal viewpoint, the model offers no evidence for the presence of a much denser, less evolved (and therefore less radiothermal) granite at depth. The area of the roof zone at depths less than 1 km is about 30 km^2 and the total volume of the model down to a depth of 9 km is about 540 km^3.

4.5.3 The rest of the batholith

As mentioned at the start of this chapter, the present 3-D interpretation was carried out partly under the auspices of the HDR geothermal project and attention was, therefore, focussed mainly on the Shap and Skiddaw granites. The western granites and the concealed batholith receive considerable attention in the later chapters of this thesis. However, there are a number of points worth making regarding the present model in the central and western Lake District.

The previous Bouguer anomaly map, based on the widely-spaced pre-1980 regional gravity data (Bott 1974), showed a single anomaly encompassing both the Skiddaw Granite and the Threlkeld Microgranite. The new data (Figure 4.1) have resolved the field into separate anomalies associated with each body and the interpretation has reflected this by placing a distinct granite cupola beneath the northeastern margin of the Threlkeld Microgranite (Figures 4.8 and 4.9). The outcrops which make up the microgranite are thought to form part of a single irregular laccolith (of density 2.67 Mg/m^3, Table 4.2) intruded into the Skiddaw Slates (Firman 1978). Neither the form of the laccolith nor its density contrast are taken into account by the present interpretation and the form of the underlying cupola is therefore uncertain.

The concealed part of the batholith is probably a composite intrusion with a range of density values (see Chapters 5, 6, 7 and 8). However, in general terms the model shows that the central part of the Lake District is underlain by a granite ridge at relatively shallow depth (< 2 km) which appears to be an extension of the Eskdale Granite. The later (early Devonian) Shap and Skiddaw granites appear to be separate bodies with steeper sides than the rest of the batholith (Figure 4.9).

The Eskdale Granite clearly extends at shallow depth beneath the Borrowdale Volcanic Group to include the Wasdale Granite. The model does not quite reach the surface over the Eskdale Granodiorite, probably because the higher density of the granodiorite is not accounted for by the density contrast of -0.13 Mg/m^3 used in the interpretation. Similarly the model just fails to reach the surface over the outcrop of the Ennerdale Granophyre. In this case the reason may be because the granophyre forms a relatively thin layer underlain by granitic rocks of a higher density, as suggested by Bott (1974).

On the north-western flank of the Ennerdale Granophyre the model includes a small granite ridge, illustrated by broken contours in Figure 4.9. The 1 km grid size and single density contrast adopted for the interpretation are not entirely suitable for defining this feature in detail. Bott's (1974) interpretation showed a shallow granite ridge in the same area which, he noted, underlies part of a belt of spotted slates. Recent mapping (Chapter 1) has shown that this belt (the Crummock Aureole) forms an ENE-trending strip, some 20 km long and up to 2.50 km wide, to the north of the Ennerdale Granophyre. The detailed interpretations discussed in Chapter 7 indicate that a dyke-like or high-level intrusion underlies much of the aureole, extending farther east than the feature shown on Figure 4.9.

The western edge of the batholith is not well resolved due to the lack of gravity data immediately offshore. The Eskdale Granite slopes steeply beneath Permo-Triassic sediments on its western flank but from the present model it is not possible to say how far the batholith continues offshore at a deeper level beneath the sedimentary sequence.

CHAPTER 5

DETAILED ANALYSIS OF DENSITY VARIATIONS

It became clear from the gravity modelling described in the previous chapter that a better understanding of the rock density variations in the Lake District is required in order to delineate the component parts of the batholith and investigate important structures within the Ordovician basement. The physical properties of the Shap and Skiddaw granites are reasonably well defined from the heat flow boreholes (Chapter 3) but density variations within and between the western instrusion are less well defined. In addition, it is necessary to take account of variations within Skiddaw and Borrowdale Volcanic groups, which overlie the concealed parts of the batholith. Although the published density data are adequate for defining bulk density values, the samples were not classified with sufficient accuracy (in terms of lithology and stratigraphy) to study variations within each group.

This chapter describes the analysis of new density determinations from over 350 localities. The samples are mainly from the western Lake District and all were classified on the basis of recent BGS geological mapping. Although the main purpose of the work was to study density variations, magnetic susceptibility and sonic velocity determinations were made on a limited number of samples. The classification, measurement and analysis techniques are discussed in Sections 5.1 to 5.3 below, and the results are discussed in Sections 5.4 to 5.8. A summary of available data for Carboniferous and Permo-Triassic rocks is given in Section 5.9. The work is published as a BGS open file report (Lee 1988, see Appendix 1)

5.1. SAMPLE COLLECTION AND CLASSIFICATION

Rock samples for the physical property determinations were obtained from a variety of sources. Samples from outcrop were collected by the author and colleagues during the course of carrying out detailed gravity surveys and the classification of these was confirmed subsequently by the BGS geologists re-mapping the area. A number of samples was loaned from the representative collections acquired by the BGS geologists during the course of re-mapping, in particular from D. Millward, A.H. Cooper, P.M. Allen, B.C. Webb, B. Young and D.J. Lawrence. In addition D.C. Cooper provided samples from collections made for geochemical analysis and D. Millward from his post-graduate research collection. The location of all sample points is shown in Figure 5.1.

In all cases every effort was made to ensure that the samples were as fresh as possible and representative of their formation and locality. Large pieces of a few granitic and volcanic rocks were collected in order to prepare cores for laboratory magnetic susceptibility and sonic velocity determinations. A portable susceptibility meter was used to record the in-situ susceptibility at a number of sites (see Section 5.2).

The samples were classified in terms of lithology and lithostratigraphy in accordance with the system developed by BGS field geologists, with certain additions and modifications by the author to enable particular groups to be identified for separate statistical analysis. The relevant codes are given in Tables 5.1 and 5.2 below.

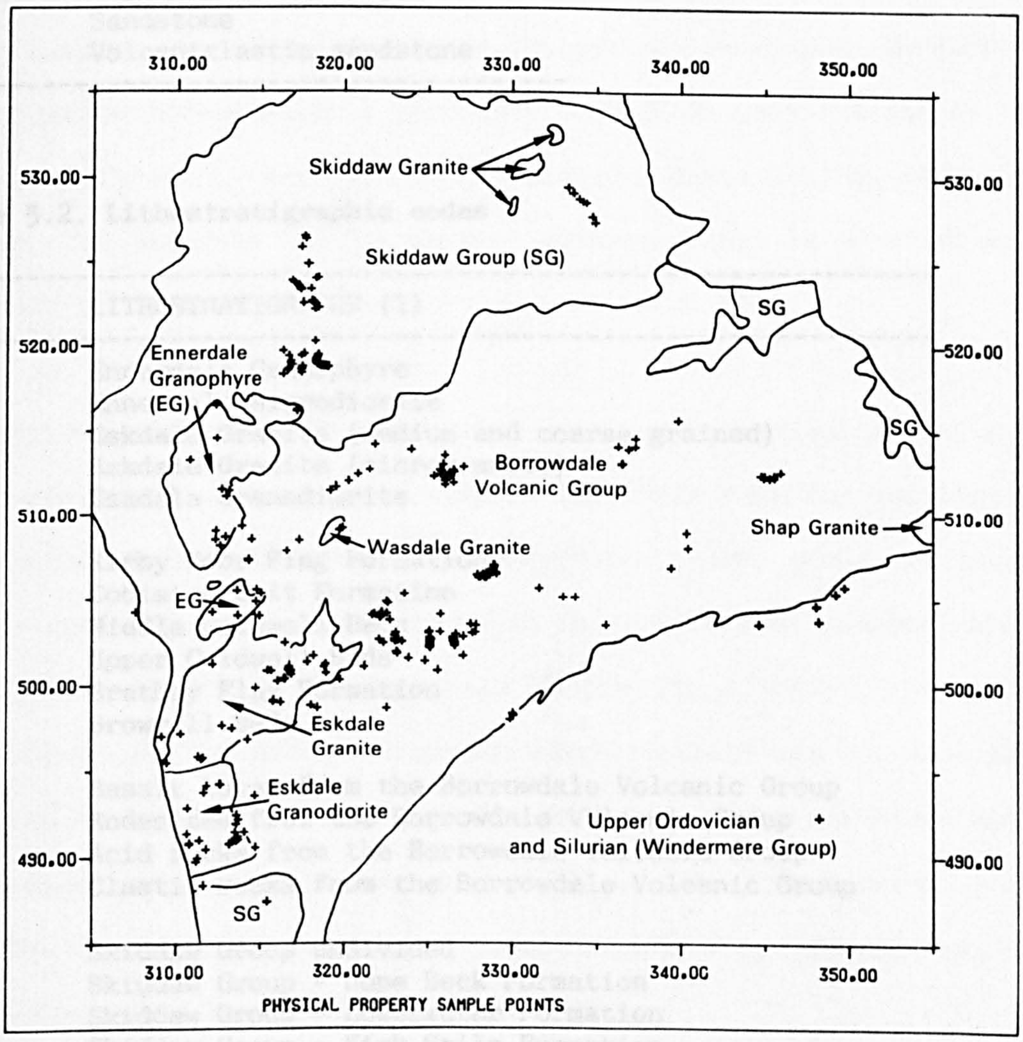


Figure 5.1 Location of physical property sample points.

Table 5.1. Lithological codes

CODE	LITHOLOGY
BASA	Basalt
DIOR	Diorite
GRGD	Granite-granodiorite family
HORN	Hornfels
IGMN	Ignimbrite
MDST	Mudstone
PYRO	Pyroclastic rock
RHAN	Rhyolite-andesite group
SDST	Sandstone
VLSS	Volcaniclastic sandstone

Table 5.2. Lithostratigraphic codes

CODE	LITHOSTRATIGRAPHY (1)
ENGP	Ennerdale Granophyre
ENNR	Ennerdale Microdiorite
ESGR	Eskdale Granite (medium and coarse grained)
ESGM	Eskdale Granite (microgranite)
ESGD	Eskdale Granodiorite
KMS	Kirby Moor Flag Formation
CTG	Coniston Grit Formation
MCW	Middle Coldwell Beds
UCW	Upper Coldwell Beds
BRS	Brathay Flag Formation
BRW	Browgill Beds
BVG1	Basalt lavas from the Borrowdale Volcanic Group
BVG2	Andesites from the Borrowdale Volcanic Group
BVG3	Acid rocks from the Borrowdale Volcanic Group
BVG4	Clastic rocks from the Borrowdale Volcanic Group
SKGP	Skiddaw Group undivided
SKHB	Skiddaw Group - Hope Beck Formation
SKLW	Skiddaw Group - Loweswater Formation
SKKS	Skiddaw Group - Kirk Stile Formation
SKLB	Skiddaw Group - Latterbarrow Formation
SKCW	Skiddaw Group from the Crummock aureole
SKSK	Skiddaw Group from the Skiddaw Granite aureole

NOTES: (1) Classifications within the Borrowdale Volcanic Group are not strictly lithostratigraphic but have been adopted for the purpose of further analysis.

5.2. PHYSICAL PROPERTY DETERMINATIONS

The measurements were carried out in the physical property laboratories at BGS Keyworth by staff of the Engineering Geology Research Group with the assistance of vacation students under the supervision of the author. Standard procedures were used throughout (see, for instance, Entwisle 1984). Saturated density, grain density and porosity were measured for all samples. Where possible, the larger field samples were broken into more manageable pieces (say 50x50x50 mm) and separate determinations were carried out on each sub-sample. The values assigned to each locality were the means of the sub-sample values. The accuracy of the density determinations is +/- 0.01 Mg/m^3 and that of the porosity determinations is +/- 0.3 %.

Cylindrical cores at least 51mm long, with parallel ground ends, were prepared from the larger samples for sonic velocity and magnetic susceptibility determinations. The compressional wave sonic velocity at 54 kHz was measured on both saturated and unsaturated samples using a Pundit Mark IV Ultrasonic Materials Tester (to a quoted accuracy of +/- 0.02 km/s). The induced magnetic susceptibility was measured using a Bison Magnetic Susceptibility System Model 3101. Two measurements were taken on each sample, one in each of the two orientations allowed by the instrument's cylindrical core-holder. The accuracy of each determination is quoted as +/- 5 %.

In addition to the laboratory susceptibility measurements, a portable Kappameter was acquired for a limited period to measure in-situ susceptibility values in the field. The procedure at each location was: (1) to check that the susceptibility was uniform, or identify a representative area by taking a number of readings over the outcrop, (2) record the mean of at least five representaive readings (corrected for surface unevenness).

5.3. DATABANK AND ANALYSIS TECHNIQUES

In order to analyse the physical property data in terms of lithology and lithostratigraphy, a format was devised for storing the data in digital form and a computer program was written to search for the relevant codes, calculate means and standard deviations, and plot histograms of density, porosity and susceptibility. The databank format and a full listing of the data held in the databank are given in Appendix 6.

The analysis program allows the user to search on lithology and/or lithostratigraphy by entering the appropriate four-letter codes (see Tables 5.1 and 5.2). Both the lithological and lithostratigraphic codes must be entered (giving a total of eight letters in all) but parts of codes or blanks are allowed. For example, an analysis of all granites and granodiorites may be performed by entering 'GRGDbbbb' and an analysis of all Borrowdale Volcanic samples may be performed by entering 'bbbbBVGb' (where b=blank). Up to four combinations of lithology and lithostratigraphy may be entered per search. Thus Eskdale medium/coarse and microgranite varieties can be selected by entering 'GRGDESGRGRGDESGM'.

Means and standard deviations are calculated for saturated density, grain density and porosity for each search. The program also calculates the theoretical saturated density at specific (user defined) porosities from the mean grain density value according to the formula:

Theoretical saturated density = ((100-POR)*GRAIN+POR)/100

[Where POR = porosity in per cent and GRAIN = grain density in Mg/m^3]

This is useful for estimating the in-situ saturated density at depth, where the porosity is likely to be lower than at the surface (see below).

Where magnetic susceptibilty determinations are available, the program calculates the mean and standard deviation, and plots a histogram of the field and laboratory values. The mean and standard deviation of the sonic velocity values are also calculated.

When interpreting the results it should be remembered that the mean saturated density will only be representative of the in-situ density if the range of porosity values is representative of the in-situ porosity. Porosity values of intrusive and extrusive igneous rocks, and deformed Lower Palaeozoic mudstones and greywackes are generally low. However, samples from outcrop sometimes have above average porosity values due to the effects of weathering or, in the case of slates, to a splitting of the slaty layers when the samples are collected. The true (in-situ) porosity, below the surface weathered layer, is probably towards (or below) the low end of the range exhibited by surface samples. Grain density values are more useful, therefore, for examining density variations related to lithology and composition.

A representative, in-situ saturated density for each formation is probably best calculated from the mean grain density and an estimated in-situ porosity value based on the observed range from surface samples. This process in necessarily somewhat subjective and is only appropriate for lithologies where a high proportion of the measured porosity is due to secondary effects. The procedure would not be appropriate for rocks such as Permo-Triassic sandstones which have high primary porosity.

5.4. THE BATHOLITH

Bott (1974 and 1978, see Table 4.1) reported density values from the Shap Granite (9 samples from 1 locality), Skiddaw Granite (8 samples from 1 locality), Threlkeld Microgranite (17 samples from 1 locality), Eskdale Granite (44 samples from 7 localities), Eskdale Granodiorite (15 samples from 2 localities) and Ennerdale Granophyre (14 samples from 2 localities). No grain density values were reported for the Eskdale and Ennerdale samples. Bott's mean saturated density values at each location are shown in Figure 5.2. The values provide a good general coverage of the exposed granitic rocks and suggest density zonation within the Eskdale Granite/granodiorite (lowest values in the centre of the intrusion) which Bott incorporated into his models of the batholith.

Since Bott's work, the properties of the Shap and Skiddaw granites have been determined from the boreholes drilled for the HDR project (see Chapter 3 for details). The work described in this section concentrates on the western granites (Eskdale and Ennerdale) with the aim of defining in more detail the density of each mapped unit and the variations across each intrusion. Samples were collected from a total of 82 localities. Field susceptibility measurements were made at 28 localities and laboratory susceptibility determinations were made on

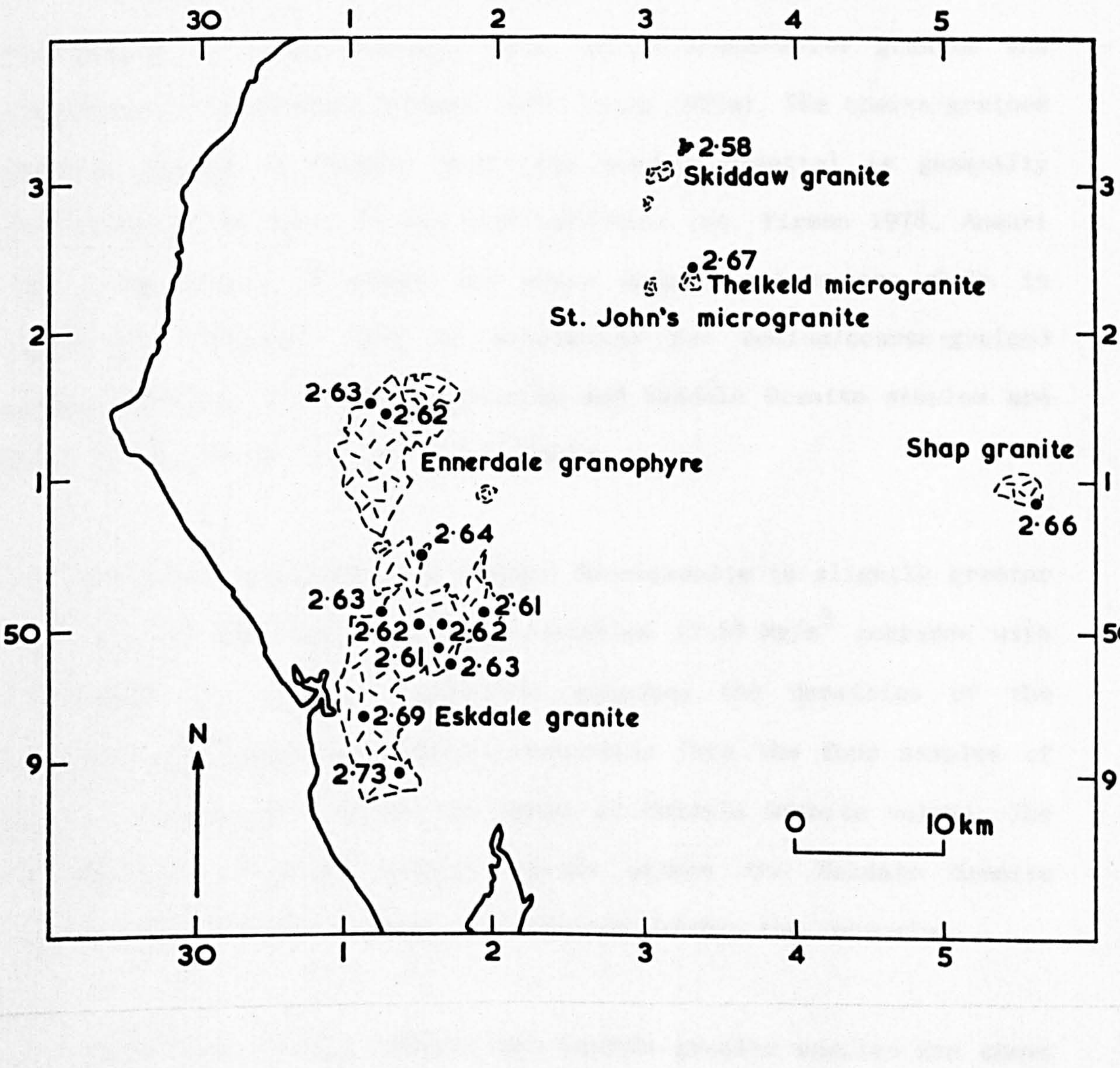


Figure 5.2 Mean saturated density values (Mg/m**3) of granitic rocks from Bott (1978).

samples from 5 localities. The results are presented below as sets of histograms corresponding to particular categories of samples. Sample locations, descriptions and property values corresponding to each set of histograms are given in Appendix 7 (Section A7.1). The data for the batholith as a whole are reviewed in Section 5.4.4.

5.4.1 Eskdale and Wasdale Granites

The principal varieties of Eskdale Granite recognized at outcrop are medium to coarse-grained, pink, perthite-muscovite granite and subordinate microgranite (Firman 1978, Young 1985a). The coarse-grained granite exposed at Wasdale Head (the Wasdale Granite) is generally considered to be part of the same intrusion (eg. Firman 1978, Ansari 1983). New sample locations and grain density values are shown in Figure 5.3. Separate sets of statistics for medium/coarse-grained Eskdale Granite, Eskdale Microgranite and Wasdale Granite samples are given in Figures 5.4 to 5.6 respectively.

The grain density of the Eskdale Microgranite is slightly greater than that of the coarser-grained varieties (2.64 Mg/m^3 compared with 2.63 Mg/m^3) but for all practical purposes the densities of the varieties are indistinguishable. Properties from the four samples of Wasdale Granite fall within the range of Eskdale Granite values. The distribution of grain density values within the Eskdale Granite (Figure 5.3) shows no evidence for zonation within the intrusion.

Statistics for all Eskdale and Wasdale granite samples are shown in Figure 5.7. The mean saturated density is 2.61 Mg/m^3 but porosity values range from 0.4% to over 4%, the higher values being from the more weathered samples. Taking a mean grain density value of 2.64 Mg/m^3

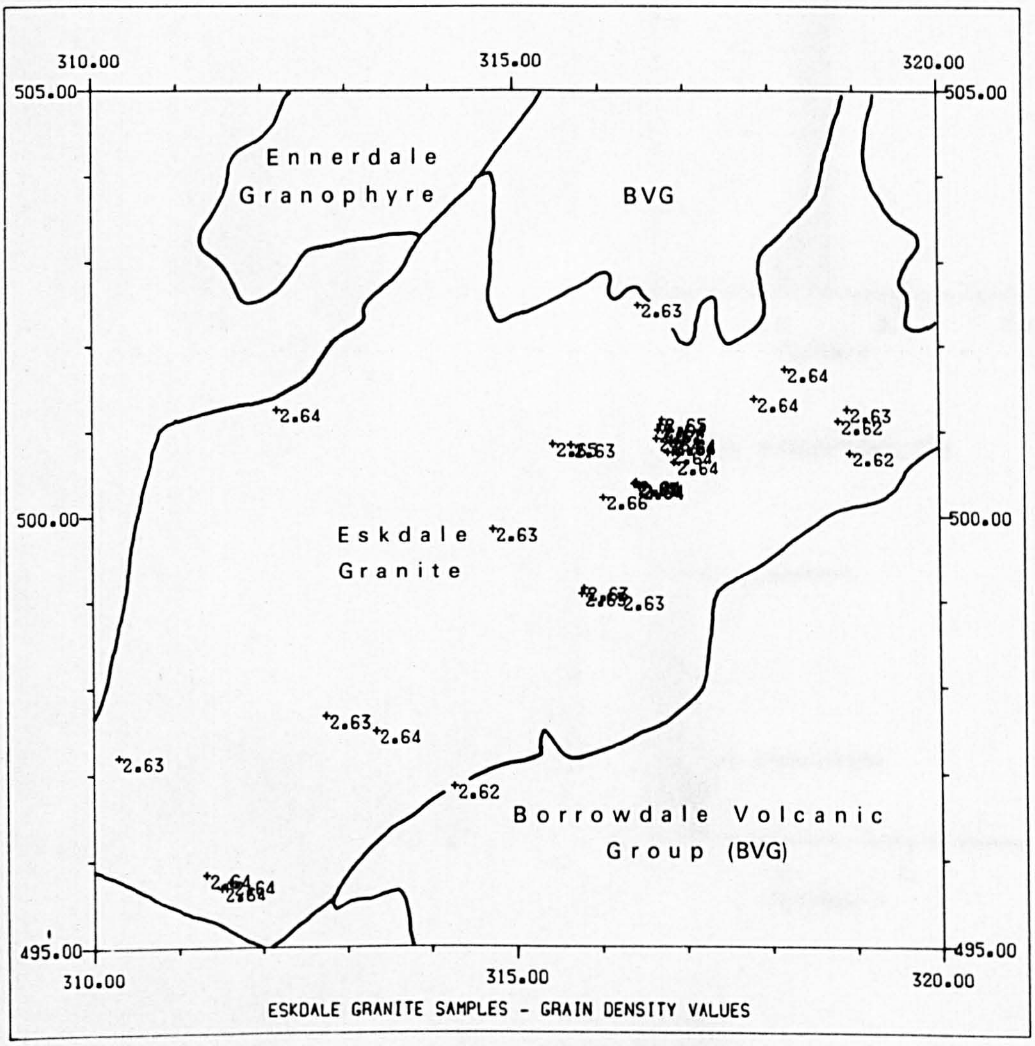
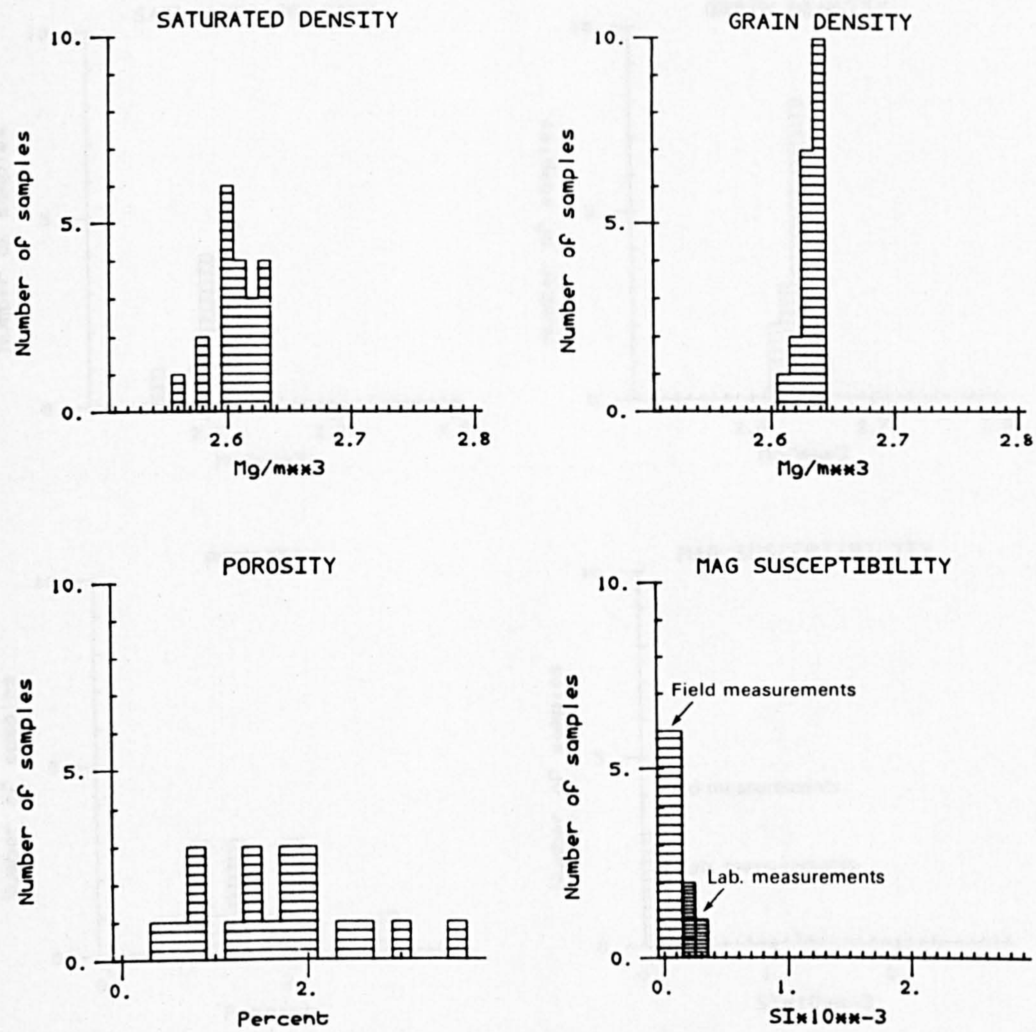


Figure 5.3 Eskdale Granite. New samples and grain density values (Mg/m**3).

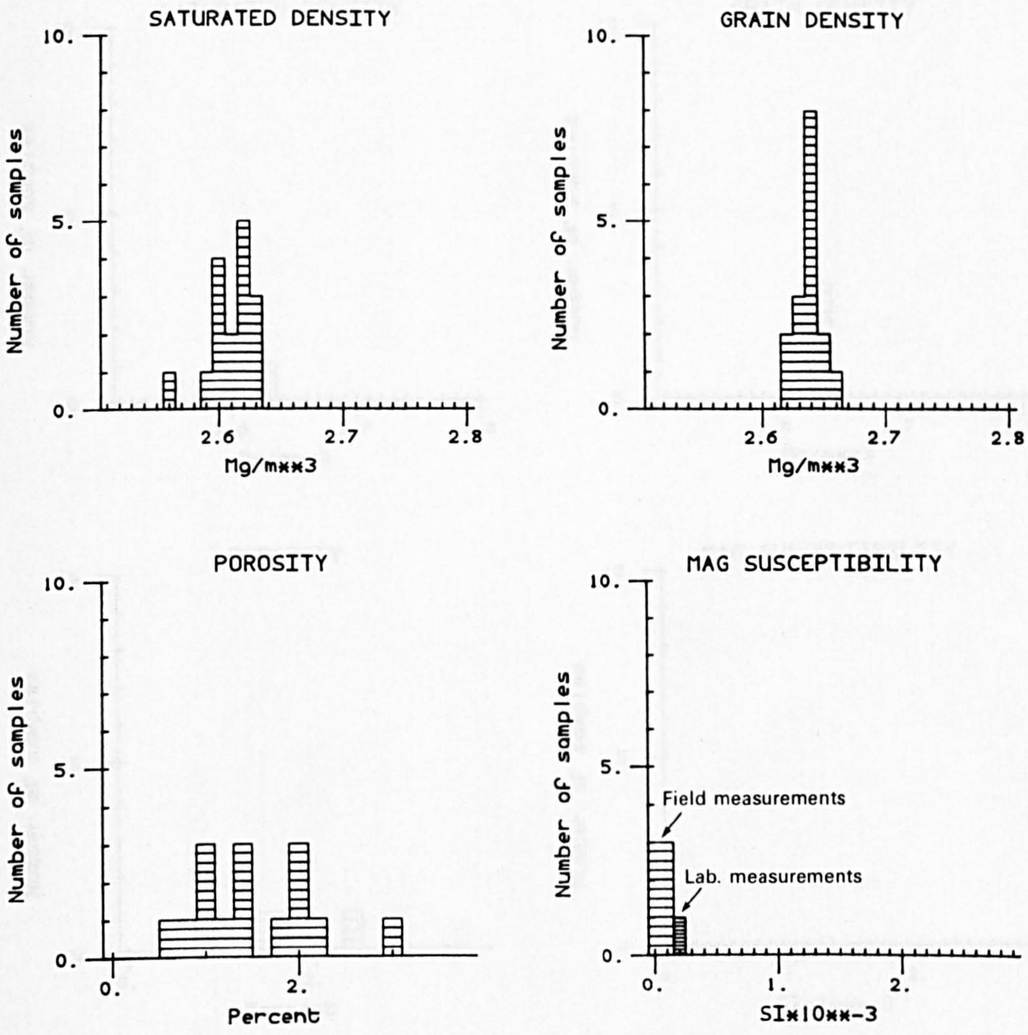
ESKDALE GRANITE (MEDIUM AND COARSE GRAINED)




```
Number of samples  =   20
Saturated density  =   2.61 +/-   0.02 Mg/m**3
Grain density      =   2.63 +/-   0.01 Mg/m**3
Porosity           =   1.64 +/-   0.82 Percent
Theoretical sat dens at  0.5 % porosity =  2.62
Theoretical sat dens at  1.0 % porosity =  2.62
3 Lab suscept meas, Mean =   0.2 +/-    0.1 SI*10**-3
13 Fld suscept meas, Mean =   0.1 +/-    0.1 SI*10**-3
3 Sonic veloc meas, Mean =   5.4 +/-    0.2 Km/sec
```

Figure 5.4 **Statistics - Eskdale Granite (medium and coarse-grained).**

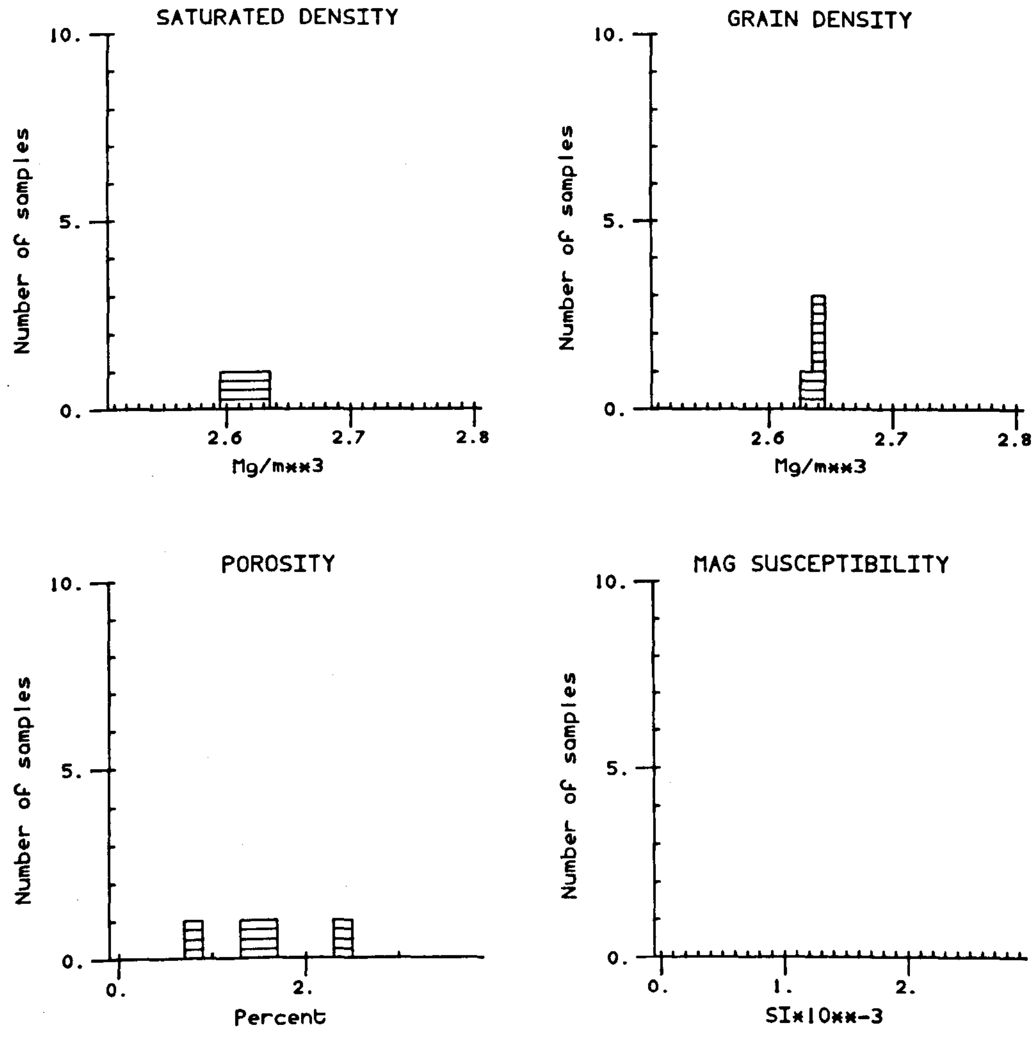
ESKDALE GRANITE (MICROGRANITE)



Number of samples - 16
Saturated density - 2.61 +/- 0.02 Mg/m**3
Grain density - 2.64 +/- 0.01 Mg/m**3
Porosity - 1.66 +/- 0.89 Percent
Theoretical sat dens at 0.5 % porosity - 2.63
Theoretical sat dens at 1.0 % porosity - 2.62
1 Lab suscept meas, Mean - 0.2 +/- 0.0 SI*10**-3
6 Fld suscept meas, Mean - 0.1 +/- 0.1 SI*10**-3
1 Sonic veloc meas, Mean - 4.5 +/- 0.0 Km/sec

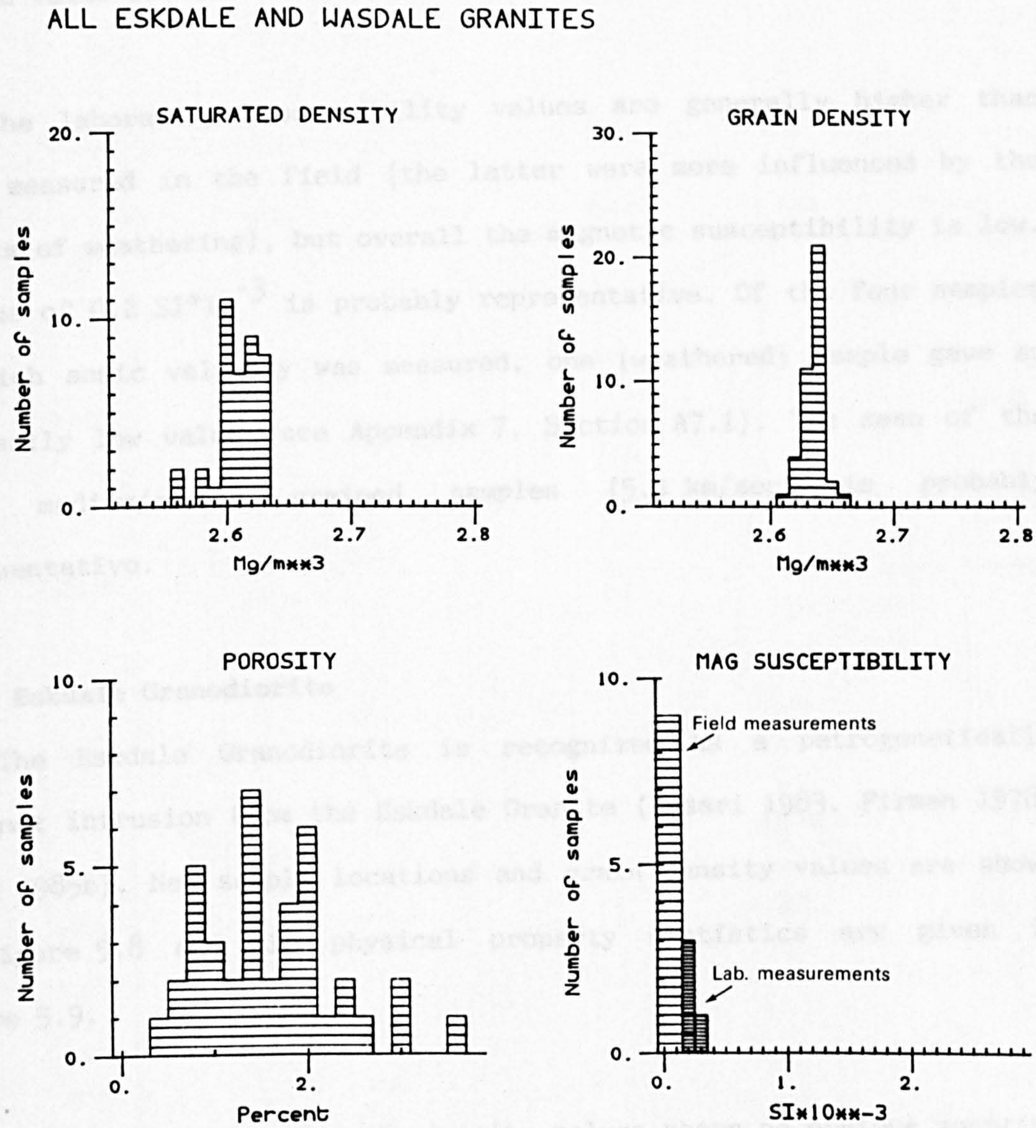
Figure 5.5 Statistics - Eskdale Granite (microgranite).

WASDALE GRANITE



Number of samples = 4
Saturated density = 2.62 +/- 0.01 Mg/m**3
Grain density = 2.64 +/- 0.00 Mg/m**3
Porosity = 1.52 +/- 0.71 Percent
Theoretical sat dens at 0.5 % porosity = 2.63
Theoretical sat dens at 1.0 % porosity = 2.62

Figure 5.6 Statistics - Wasdale Granite.



Number of samples = 40
Saturated density = 2.61 +/- 0.02 Mg/m**3
Grain density = 2.64 +/- 0.01 Mg/m**3
Porosity = 1.64 +/- 0.82 Percent
Theoretical sat dens at 0.5 % porosity = 2.63
Theoretical sat dens at 1.0 % porosity = 2.62
4 Lab suscept meas, Mean = 0.2 +/- 0.1 SI*10**-3
19 Fld suscept meas, Mean = 0.1 +/- 0.1 SI*10**-3
4 Sonic veloc meas, Mean = 5.2 +/- 0.5 Km/sec

Figure 5.7 Statistics - All Eskdale and Wasdale granites.

and assuming a porosity value at the low end of the range (say 0.5%) for granite below the weathered surface layer, gives a representative in-situ value for the Eskdale/Wasdale intrusion of 2.63 Mg/m^3.

The laboratory susceptibility values are generally higher than those measured in the field (the latter were more influenced by the effects of weathering), but overall the magnetic susceptibility is low. A value of 0.2 $SI*10^{-3}$ is probably representative. Of the four samples on which sonic velocity was measured, one (weathered) sample gave an abnormally low value (see Appendix 7, Section A7.1). The mean of the three medium/coarse grained samples (5.4 km/sec) is probably representative.

5.4.2 Eskdale Granodiorite

The Eskdale Granodiorite is recognized as a petrogenetically distinct intrusion from the Eskdale Granite (Ansari 1983, Firman 1978, Young 1985b). New sample locations and grain density values are shown in Figure 5.8 and the physical property statistics are given in Figure 5.9.

The distribution of grain density values shows no obvious zonation of density across the intrusion. Grain densities are mostly in the range 2.68 to 2.74 Mg/m^3 with a strong peak at 2.71 Mg/m^3; the only exceptions are two values around 2.60 Mg/m^3. The in-situ saturated density based on the mean grain density and a porosity of 0.5% is 2.69 Mg/m^3. However, if the two abnormally low values are excluded, a value of 2.70 Mg/m^3 is probably more representative. Only four field susceptibility values were recorded. They are marginally higher than the field values from the main Eskdale Granite.

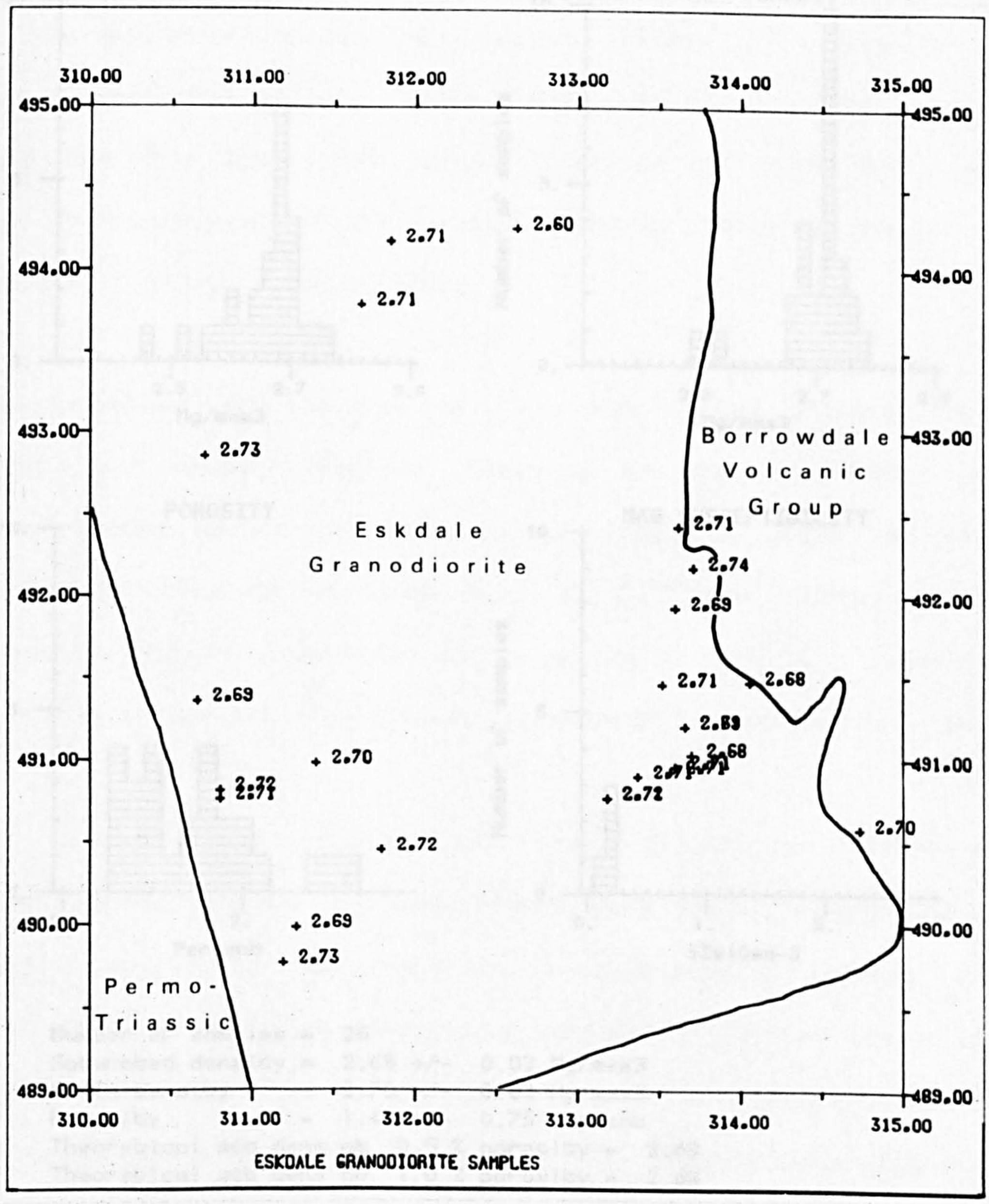
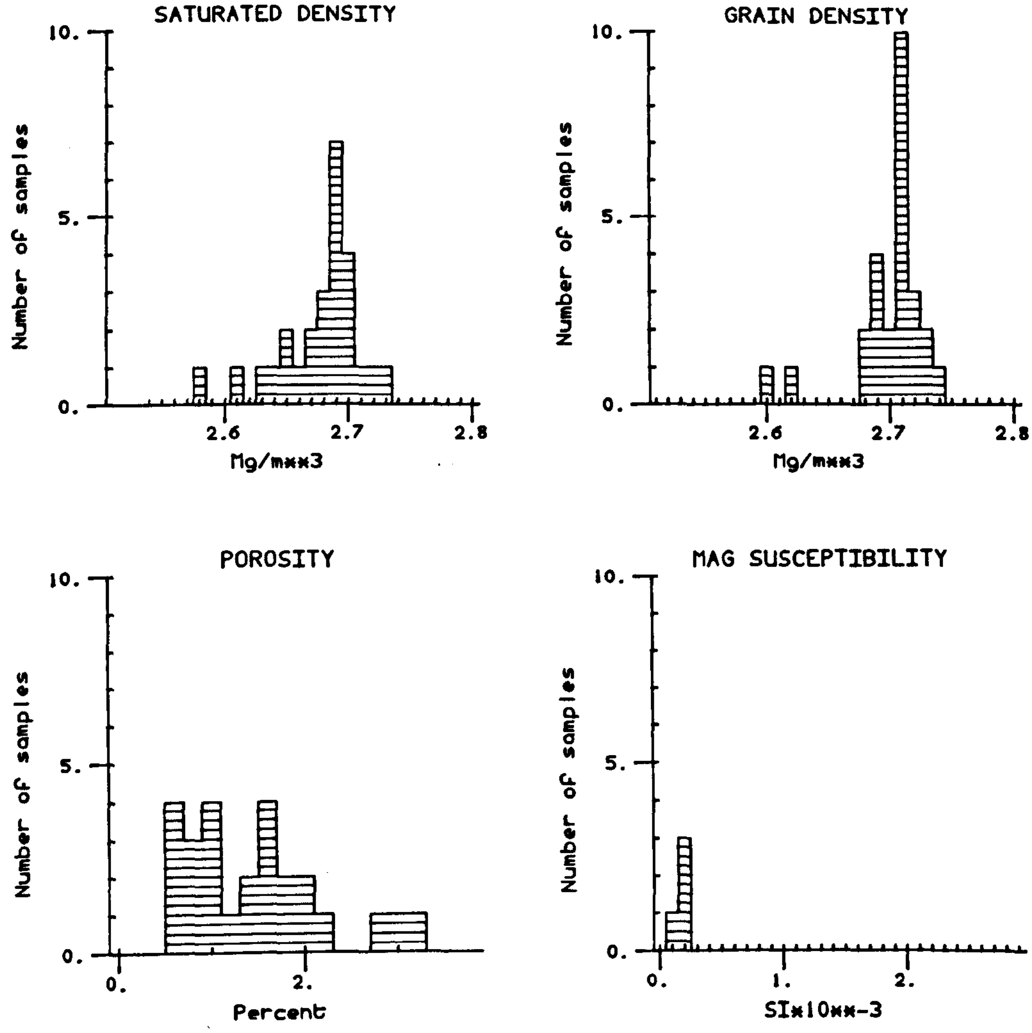


Figure 5.8 Eskdale Granodiorite. New samples and grain density values (Mg/m**3).

ESKDALE GRANODIORITE



Number of samples = 26
Saturated density = 2.68 +/- 0.03 Mg/m**3
Grain density = 2.70 +/- 0.03 Mg/m**3
Porosity = 1.44 +/- 0.75 Percent
Theoretical sat dens at 0.5 % porosity = 2.69
Theoretical sat dens at 1.0 % porosity = 2.68

4 Fld suscept meas, Mean = 0.2 +/- 0.1 SI*10**-3

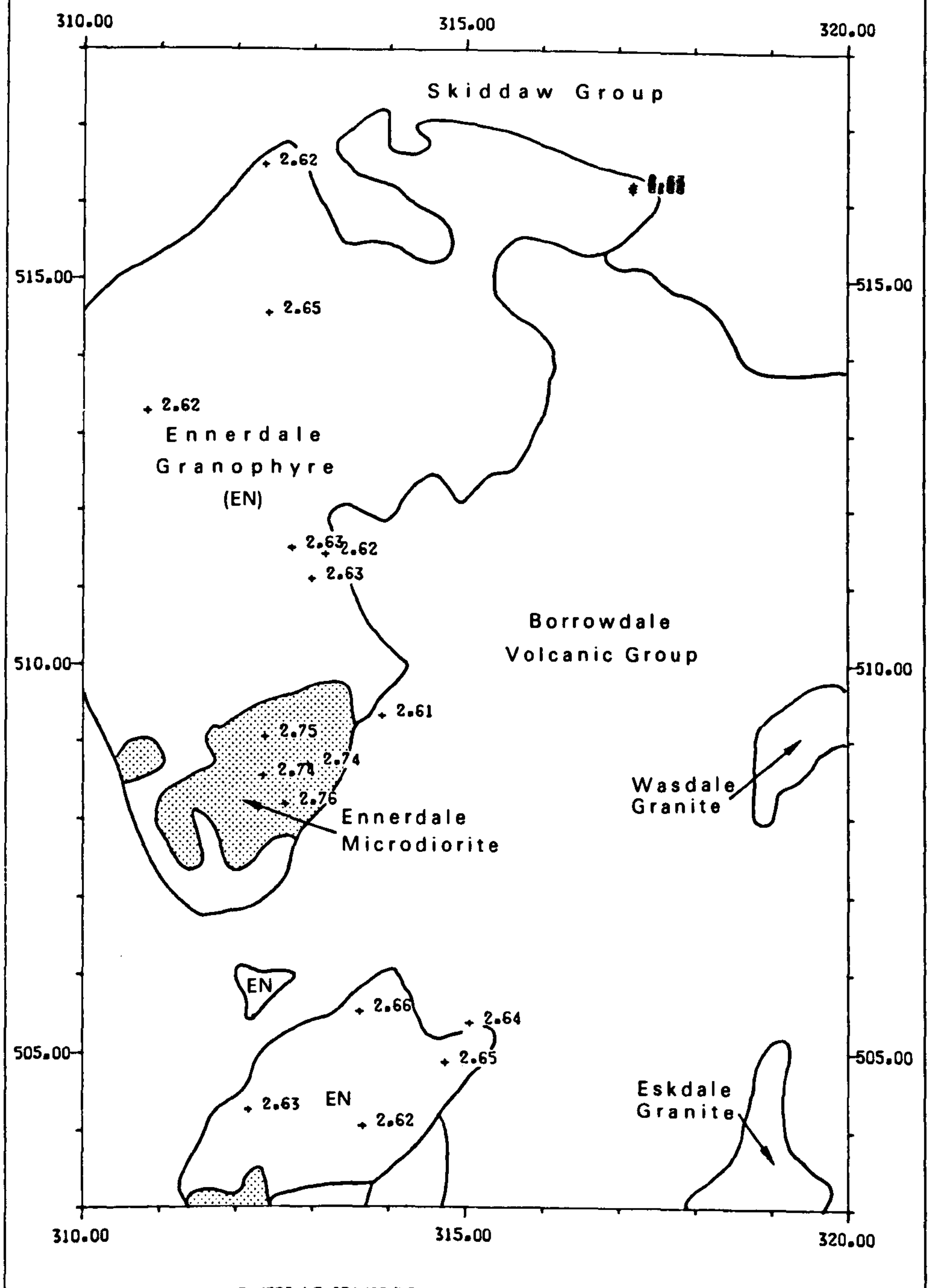
Figure 5.9 Statistics - Eskdale Granodiorite.

5.4.3 Ennerdale Granophyre and Microdiorite

The bulk of the Ennerdale Granophyre consists of a fine-grained, pink, quartz-alkali feldspar rock (Firman 1978). It crops out over a large area around Ennerdale and in a smaller outcrop to the north of the Eskdale Granite (Figure 1.3). Separate diorites, xenolithic and hybrid rocks are common within the intrusion (Firman 1978). Samples of a common microdiorite variety, known locally as 'Needle Rock', were collected from four localities. Sample locations and grain densities are shown in Figure 5.10 and the physical property statistics are shown in Figures 5.11 and 5.12 respectively.

Density values from the granophyre are very similar to those from the Eskdale and Wasdale Granites. There is no obvious evidence of density variation across the outcrop. A reasonable value for the in-situ density below the weathered layer is 2.62 Mg/m^3 (based on the mean grain density of 2.63 Mg/m^3 and a porosity of 0.5%). Magnetic susceptibility values are also similar to those of the Eskdale Granite.

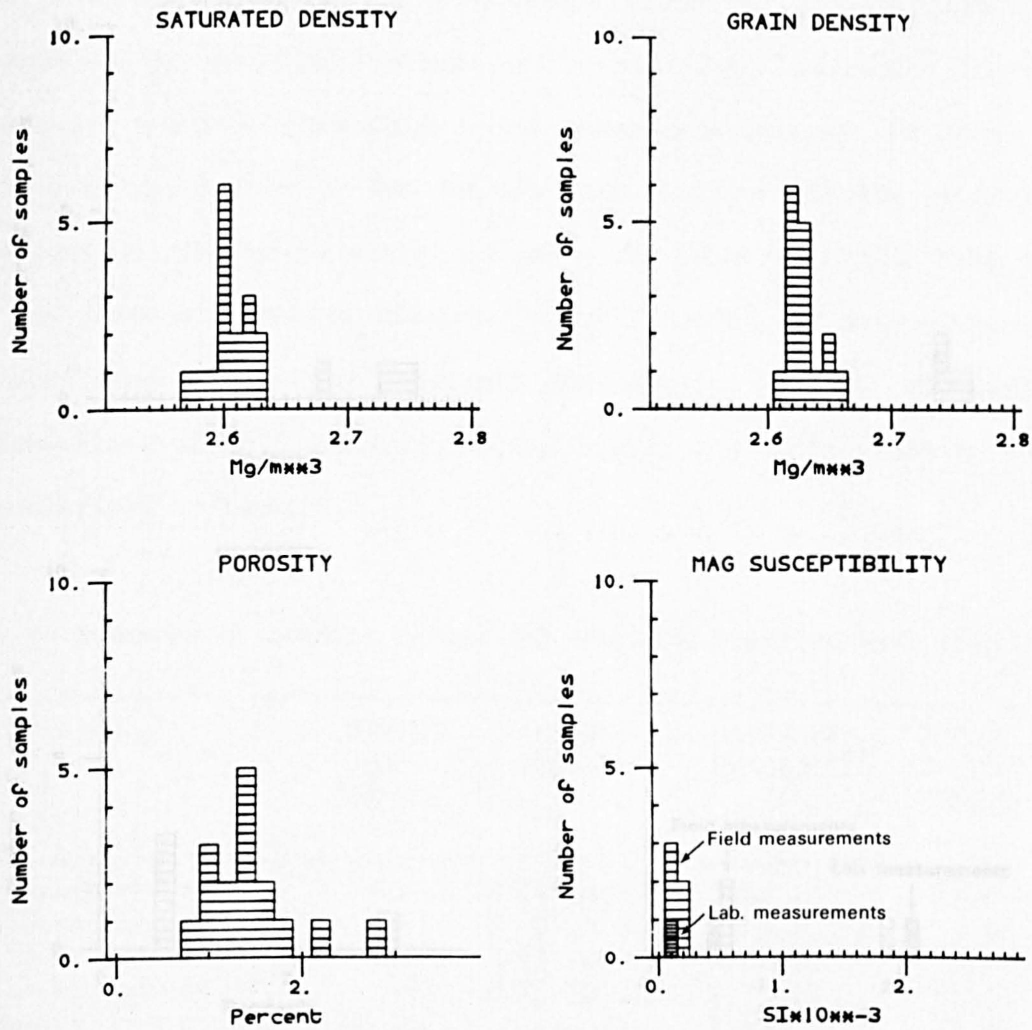
The microdiorite (Figure 5.12) has distinctly different properties. Density values are much higher, and if the single value with high porosity is excluded, the mean saturated density is 2.74 Mg/m^3 (at 0.5% porosity). Magnetic susceptibility values are up to 100 times greater than those of the granite (note the different scale on the susceptibility histogram in Figure 5.12). These highly magnetic rocks are almost certainly the cause of the aeromagnetic anomaly observed over the Ennerdale Granophyre (see Section 2.3, Figure 2.7).



ENNERDALE GRANOPHYRE AND MICRODIORITE SAMPLES

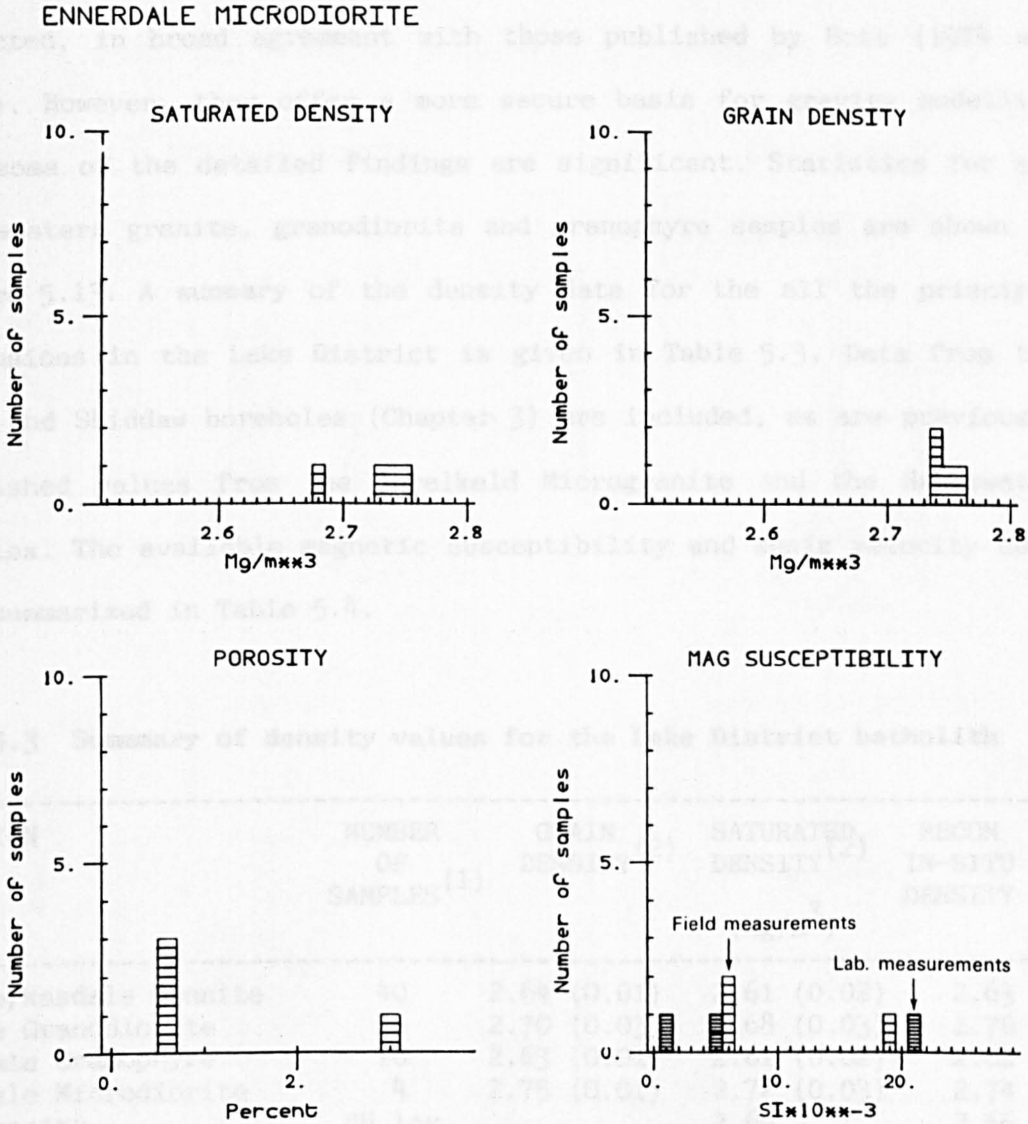
Figure 5.10 Ennerdale Granophyre and Microdiorite. New samples and grain density values (Mg/m**3).

ENNERDALE GRANOPHYRE



Number of samples - 16
Saturated density - 2.61 +/- 0.02 Mg/m**3
Grain density - 2.63 +/- 0.01 Mg/m**3
Porosity - 1.39 +/- 0.51 Percent
Theoretical sat dens at 0.5 % porosity - 2.62
Theoretical sat dens at 1.0 % porosity - 2.61
1 Lab suscept meas, Mean - 0.1 +/- 0.0 SI*10**-3
5 Fld suscept meas, Mean - 0.1 +/- 0.1 SI*10**-3
1 Sonic veloc meas, Mean - 5.6 +/- 0.0 Km/sec

Figure 5.11 Statistics - Ennerdale Granophyre.



Number of samples = 4
Saturated density = 2.72 +/- 0.03 Mg/m**3
Grain density = 2.75 +/- 0.01 Mg/m**3
Porosity = 1.10 +/- 1.20 Percent
Theoretical sat dens at 0.5 % porosity = 2.74
Theoretical sat dens at 1.0 % porosity = 2.73
3 Lab suscept meas, Mean = 9.0 +/- 10.5 SI*10**-3
4 Fld suscept meas, Mean = 9.0 +/- 6.4 SI*10**-3
3 Sonic veloc meas, Mean = 6.1 +/- 0.1 Km/sec

Figure 5.12 Statistics - Ennerdale Microdiorite.

5.4.4 Overview of the batholith

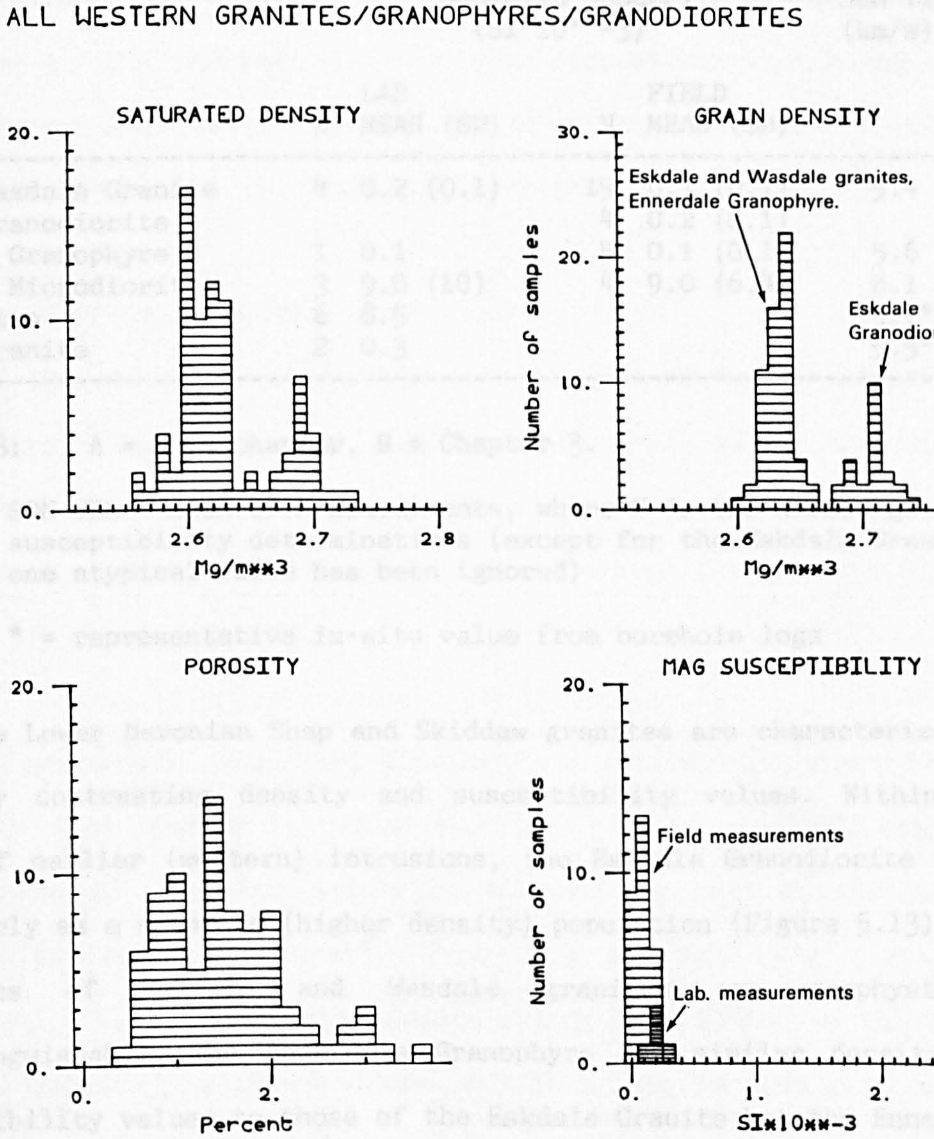
The new density values for the western granites are, as would be expected, in broad agreement with those published by Bott (1974 and 1978). However, they offer a more secure basis for gravity modelling and some of the detailed findings are significant. Statistics for all the western granite, granodiorite and granophyre samples are shown in Figure 5.13. A summary of the density data for the all the principal intrusions in the Lake District is given in Table 5.3. Data from the Shap and Skiddaw boreholes (Chapter 3) are included, as are previously published values from the Threlkeld Microgranite and the Haweswater Complex. The available magnetic susceptibility and sonic velocity data are summarized in Table 5.4.

Table 5.3 Summmary of density values for the Lake District batholith

INTRUSION	NUMBER OF SAMPLES (1)	GRAIN DENSITY (2)	SATURATED DENSITY (2) (Mg/m^3)	RECOM IN-SITU DENSITY	SOURCE
Eskdale/Wasdale Granite	40	2.64 (0.01)	2.61 (0.02)	2.63	A
Eskdale Granodiorite	26	2.70 (0.03)	2.68 (0.03)	2.70	A
Ennerdale Granophyre	16	2.63 (0.01)	2.61 (0.02)	2.62	A
Ennerdale Microdiorite	4	2.75 (0.01)	2.72 (0.03)	2.74	A
Shap Granite	BH log		2.66	2.66	B
Skiddaw Granite	BH log		2.58-2.67	2.63	B
Threlkeld Microgranite	17	2.70 (0.01)	2.67 (0.03)		C
Haweswater Complex (3)	10	2.72-2.88	2.70-2.86		D

NOTES: (1) One representative sample per location unless otherwise specified.
(2) Values given are the mean and standard deviation or range.
(3) Range for dolerites and gabbros.

REFERENCES: A = This chapter.
B = Chapter 3.
C = Bott (1974), 17 samples from a single location.
D = Lee (1984a), see Chapter 4.



Number of samples = 82
Saturated density = 2.63 +/- 0.04 Mg/m**3
Grain density = 2.65 +/- 0.04 Mg/m**3
Porosity = 1.53 +/- 0.75 Percent
Theoretical sat dens at 0.5 % porosity = 2.65
Theoretical sat dens at 1.0 % porosity = 2.64
5 Lab suscept meas, Mean = 0.2 +/- 0.1 SI*10**-3
28 Fld suscept meas, Mean = 0.1 +/- 0.1 SI*10**-3
5 Sonic veloc meas, Mean = 5.3 +/- 0.5 Km/sec

Figure 5.13 Statistics - All western granites, granophyres and granodiorites.

Table 5.4 Summmary of magnetic susceptibility and sonic velocity data for the Lake District batholith.

FORMATION	MAGNETIC SUSCEPT (SI*10**-3)				SON VEL (km/s)	SOURCE
	LAB		FIELD			
	N	MEAN (SD)	N	MEAN (SD)		
Eskdale/Wasdale Granite	4	0.2 (0.1)	19	0.1 (0.1)	5.4	A
Eskdale Granodiorite			4	0.2 (0.1)		A
Ennerdale Granophyre	1	0.1	5	0.1 (0.1)	5.6	A
Ennerdale Microdiorite	3	9.0 (10)	4	9.0 (6.4)	6.1	A
Shap Granite	6	8.5			5.7*	B
Skiddaw Granite	2	0.3			5.5*	B

REFERENCES: A = This chapter, B = Chapter 3.

NOTES: SON VEL = mean of N measurments, where N is the number given for lab susceptibility determinations (except for the Eskdale Granite, where one atypical value has been ignored)

* = representative in-situ value from borehole logs

The Lower Devonian Shap and Skiddaw granites are characterized by markedly contrasting density and susceptibility values. Within the group of earlier (western) intrusions, the Eskdale Granodiorite shows up clearly as a separate (higher density) population (Figure 5.13). The varieties of Eskdale and Wasdale granites are geophysically indistinguishable. The Ennerdale Granophyre has similar density and susceptibility values to those of the Eskdale Granite but the Ennerdale Microdiorite has a higher density and is strongly magnetic.

When grain density values are examined in relation to sample location, the data offer no convincing evidence for density variations across the Eskdale and Ennerdale intrusions (Figures 5.3, 5.8 and 5.10). This is particularly important in the western part of the Lake District, where Bott assumed a sub-vertically zoned batholith with density values increasing from 2.61 Mg/m^3 in Eskdale to 2.68 Mg/m^3 on the northern margin. Although density values presumably must increase towards the margins of the batholith to explain the shape of the gravity anomaly (Bott 1974), a fine zonation of the intrusions is not supported by the physical property data. An alternative possibility, that the variation may be in the form of a series of major intrusions (batholith components) is discussed in Chapter 7.

5.5. THE BORROWDALE VOLCANIC GROUP

The Borrowdale Volcanic Group overlies the concealed batholith in the central Lake District. The volcanic pile shows considerable compositional diversity, comprising basaltic to rhyolitic lavas, welded ignimbrites, primary and reworked tuff and coarse to fine breccia (see Chapter 1).

The previously published density data reflect the compositional diversity (see Chapter 4, Tables 4.1 and 4.2). Bott (1974) reported values from 12 locations mainly in the western part of the outcrop ranging in saturated density from 2.66 to 2.80 Mg/m^3 (mean of localities = 2.74 Mg/m^3). The present author (Lee 1984a and Table 4.1) reported values from 15 locations mainly in the eastern part of the outcrop ranging from 2.69 to 2.87 Mg/m^3 (mean of localities = 2.75 Mg/m^3). While these measurements give a reasonable value for the average (bulk) density of the Borrowdale Volcanic rocks, the relative proportions of the various lithologies are not consistent throughout the pile and there are thick sequences of both basic and acid rocks whose effects should be taken into account in gravity modelling (for example, the thick sequence of acid ignimbrite in the central fells (the Airy's Bridge Formation, Oliver 1961).

The task of calculating representative densities for the Borrowdale Volcanic Group presents a somewhat different problem to that of the batholith. Each formation in the sequence comprises different lithologies in different proportions. To determine formation densities by collecting representative suites of samples from each formation was considered a difficult, if not impossible task. The procedure adopted, therefore, was as follows:

(1) The four principal lithological types in the volcanic pile were identified and the average (representative) densitiy of each was determined (the four lithological types are defined in Table 5.5).

(2) The volcanic sequence was divided into a series of formational groupings (composite formations), each with a characteristic mix of lithologies (see Section 1.2.2). These are indicated on Figure 1.7 and their distribution at outcrop is shown in Figure 1.3

(3) A representative density for each composite formation was calculated from the relative proportion of each lithology in that formation.

The analysis was carried out in close collaboration with D. Millward (BGS) who advised on the division of lithologies into the four compositional groups and provided information on the relative proportion of each lithology in each part of the sequence (from recent mapping, published data and his post-graduate research).

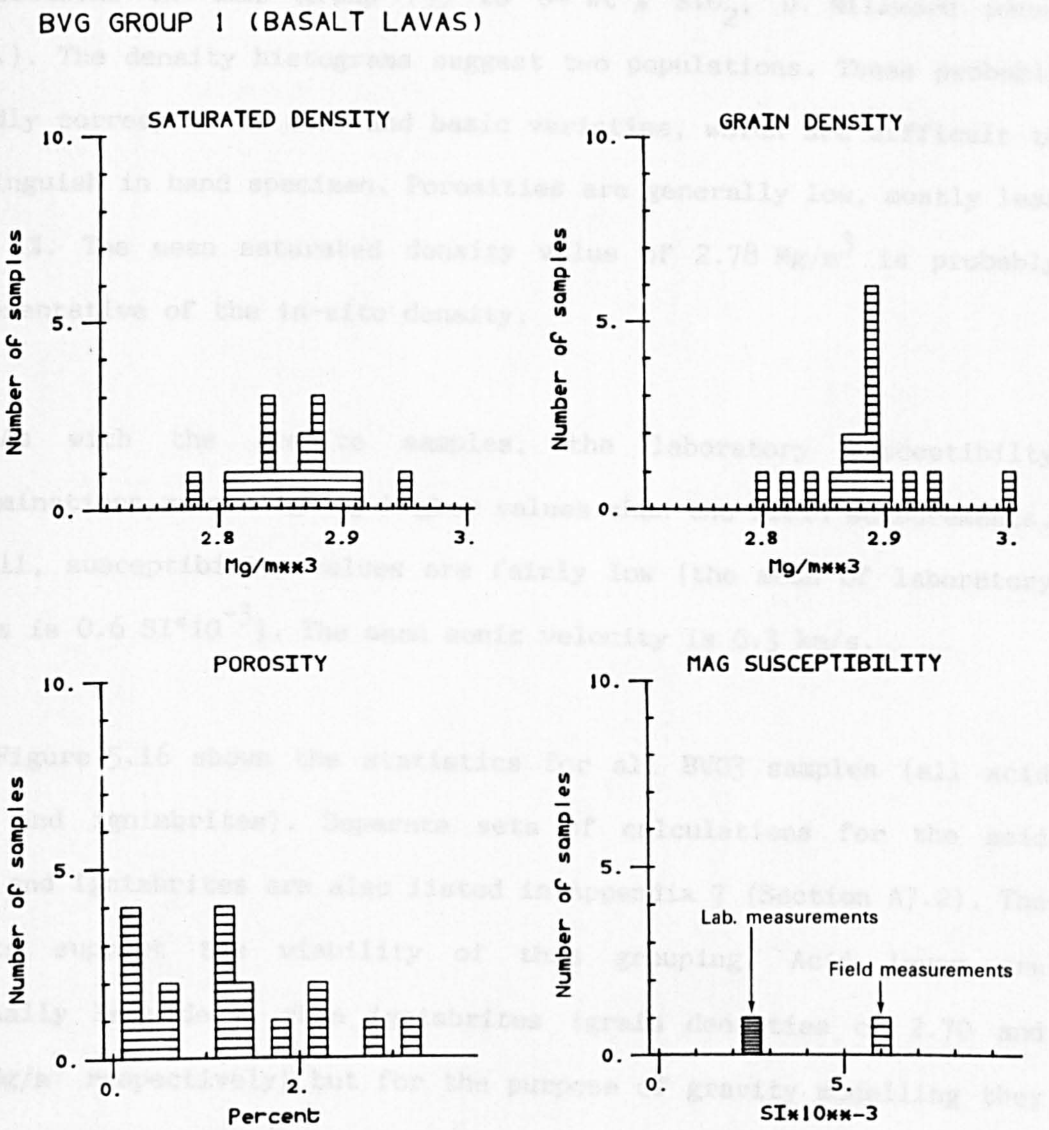
Table 5.5 Lithological subdivisions of the Borrowdale Volcanic Group.

GROUP	DESCRIPTION
BVG1	Basalt lavas.
BVG2	Andesites. This covers a wide range of compositions but it is not possible to subdivide the the group on the basis of hand specimens.
BVG3	Acid rocks. Includes rhyolitic to rhyodacitic welded ignimbrite sheets and lavas/sills.
BVG4	Clastic rocks. Includes coarse to fine breccia, primary tuff and reworked tuff (sometimes referred to as volcaniclastic sandstone). The group encompasses a large range of compositions but most appear to be dacitic/andesitic.

Samples from 166 locations (see Figure 5.1), representing the four lithological groupings, were collected, or provided by the BGS geologists re-mapping the area. Field susceptibility measurements were made at 52 locations and cores from 19 locations were collected for laboratory susceptibility and sonic velocity determinations. The results from the four lithological groups are discussed in Section 5.5.1 and the calculated formation densities are discussed in Section 5.5.2. Complete listings corresponding to each set of histograms (ie. each search of the database) are given in Appendix 7 (Section A7.2).

5.5.1 Analysis by lithology

Statistics for BVG1 (basalt lavas) are given in Figure 5.14. As expected, density values are high, with a mean grain density of 2.88 Mg/m^3. Porosity values range from 0.1% to over 3%. The theoretical in-situ saturated density, based on the mean grain density and a porosity of 0.5%, is 2.88 Mg/m^3.



Number of samples = 18
Saturated density = 2.86 +/- 0.04 Mg/m**3
Grain density = 2.88 +/- 0.04 Mg/m**3
Porosity = 1.18 +/- 0.95 Percent
Theoretical sat dens at 0.5 % porosity = 2.88
Theoretical sat dens at 1.0 % porosity = 2.87
1 Lab suscept meas, Mean = 2.4 +/- 0.0 SI*10**-3
1 Fld suscept meas, Mean = 6.1 +/- 0.0 SI*10**-3
1 Sonic veloc meas, Mean = 6.4 +/- 0.0 Km/sec

Figure 5.14 **Statistics - Borrowdale Volcanic Group: BVG1 (basalt lavas)**

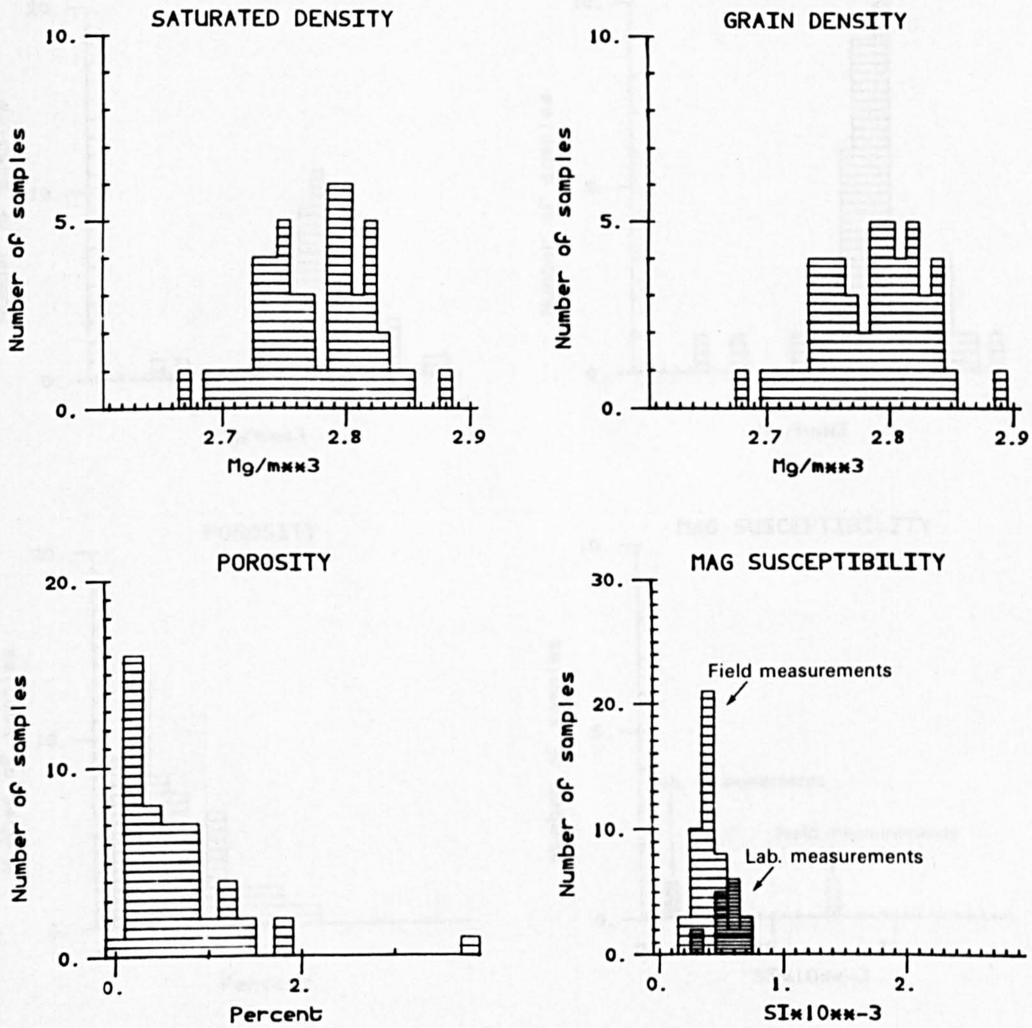
Statistics for BVG2 (andesites) are given in Figure 5.15. Grain density values cover a wide range, as anticipated from the range of compositions in this group (55 to 64 wt % SiO_2, D. Millward pers. comm.). The density histograms suggest two populations. These probably broadly correspond to acid and basic varieties, which are difficult to distinguish in hand specimen. Porosities are generally low, mostly less than 1%. The mean saturated density value of 2.78 Mg/m^3 is probably representative of the in-situ density.

As with the granite samples, the laboratory susceptibilty determinations give slightly higher values than the field measurements. Overall, susceptibility values are fairly low (the mean of laboratory values is 0.6 $SI*10^{-3}$). The mean sonic velocity is 6.3 km/s.

Figure 5.16 shows the statistics for all BVG3 samples (all acid lavas and ignimbrites). Separate sets of calculations for the acid lavas and ignimbrites are also listed in Appendix 7 (Section A7.2). The results support the viability of this grouping. Acid lavas are marginally less dense than ignimbrites (grain densities of 2.70 and 2.71 Mg/m^3 respectively) but for the purpose of gravity modelling they can be treated as a single unit. An in-situ value of 2.70 Mg/m^3 is considered to be representative of the group as a whole but a value of 2.69 Mg/m^3 may be more appropriate for formations comprising mainly acid lavas.

Figure 5.17 shows the statistics for all BVG4 samples (clastic rocks). Separate sets of calculations for the reworked volcanic rocks (volcaniclastic sandstone) and tuffs are listed in Appendix 7 (Section A7.2). The range of densities for the reworked volcanic rocks

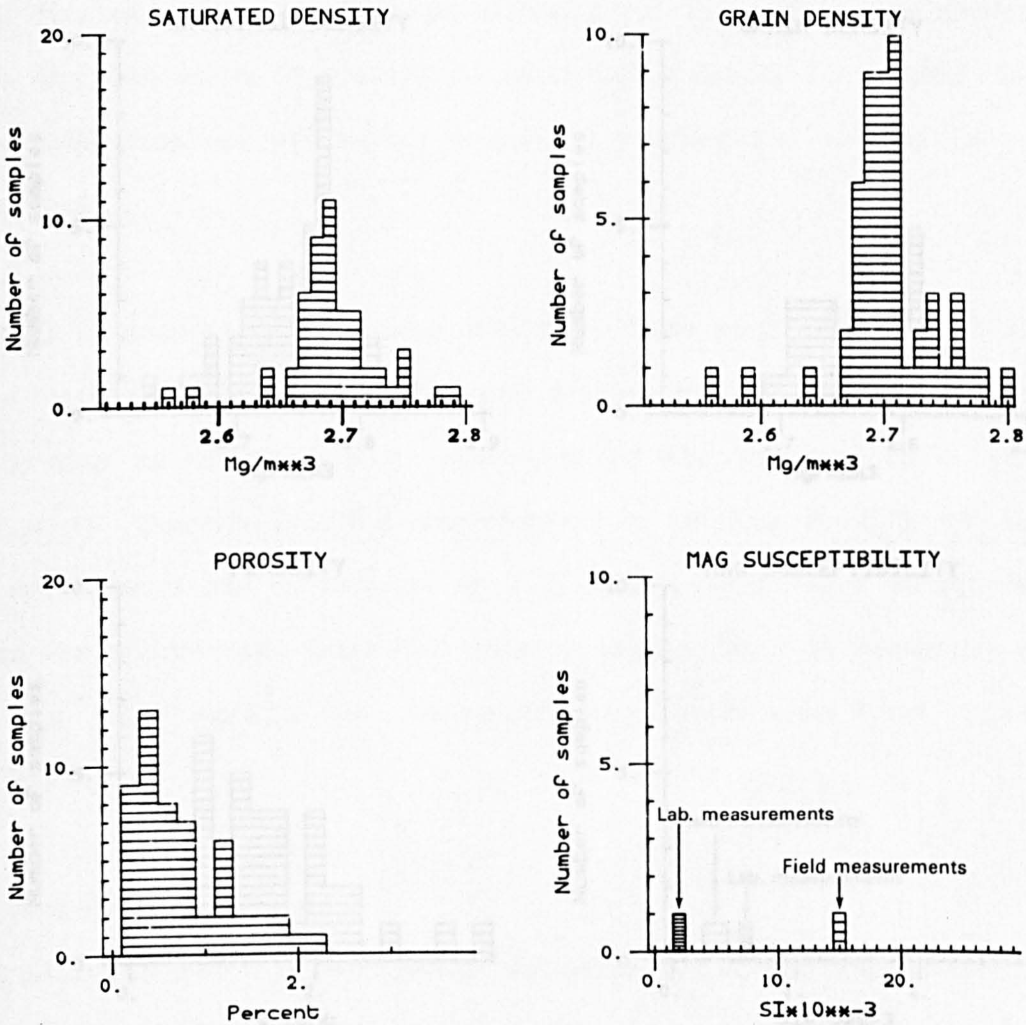
BVG GROUP 2 (ANDESITES)



Number of samples = 50
Saturated density = 2.78 +/- 0.04 Mg/m**3
Grain density = 2.79 +/- 0.04 Mg/m**3
Porosity = 0.61 +/- 0.63 Percent
Theoretical sat dens at 0.2 % porosity = 2.78
Theoretical sat dens at 0.5 % porosity = 2.78
16 Lab suscept meas, Mean = 0.6 +/- 0.1 SI*10**-3
47 Fld suscept meas, Mean = 0.4 +/- 0.1 SI*10**-3
16 Sonic veloc meas, Mean = 6.3 +/- 0.2 Km/sec

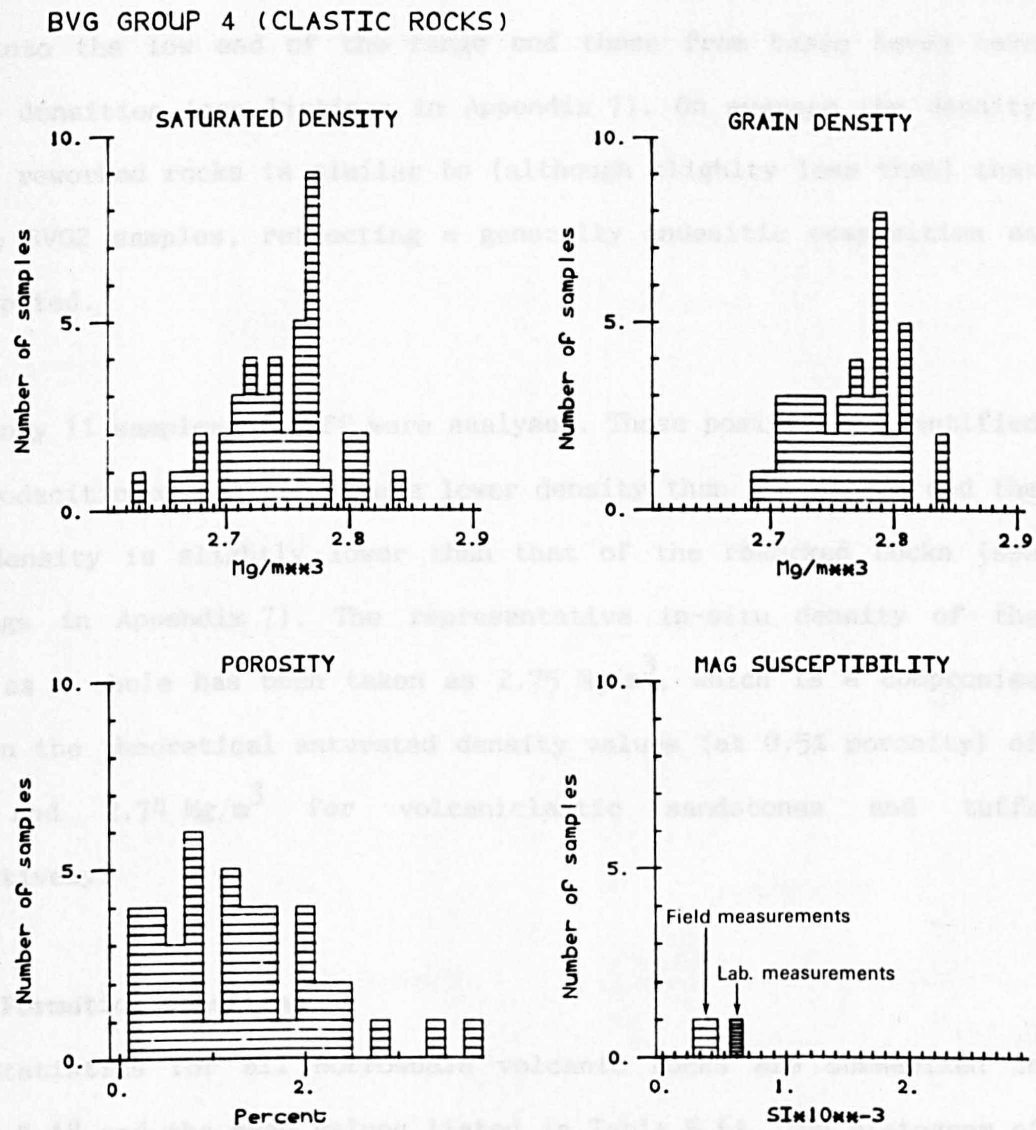
Figure 5.15 Statistics - Borrowdale Volcanic Group: BVG2 (andesites)

BVG GROUP 3 (ACID ROCKS - LAVAS AND IGNIMBRITES)



Number of samples	=	53
Saturated density	=	2.69 +/- 0.04 Mg/m**3
Grain density	=	2.71 +/- 0.04 Mg/m**3
Porosity	=	0.71 +/- 0.53 Percent
Theoretical sat dens at 0.2 % porosity	=	2.70
Theoretical sat dens at 0.5 % porosity	=	2.70
1 Lab suscept meas, Mean	=	2.2 +/- 0.0 SI*10**-3
1 Fld suscept meas, Mean	=	14.8 +/- 0.0 SI*10**-3
1 Sonic veloc meas, Mean	=	6.4 +/- 0.0 Km/sec

Figure 5.16 **Statistics - Borrowdale Volcanic Group: BVG3 (acid lavas and ignimbrites)**



Number of samples = 43
Saturated density = 2.74 +/- 0.04 Mg/m**3
Grain density = 2.77 +/- 0.04 Mg/m**3
Porosity = 1.30 +/- 0.87 Percent
Theoretical sat dens at 0.2 % porosity = 2.76
Theoretical sat dens at 0.5 % porosity = 2.76
1 Lab suscept meas, Mean = 0.6 +/- 0.0 SI*10**-3
2 Fld suscept meas, Mean = 0.4 +/- 0.1 SI*10**-3
1 Sonic veloc meas, Mean = 6.3 +/- 0.0 Km/sec

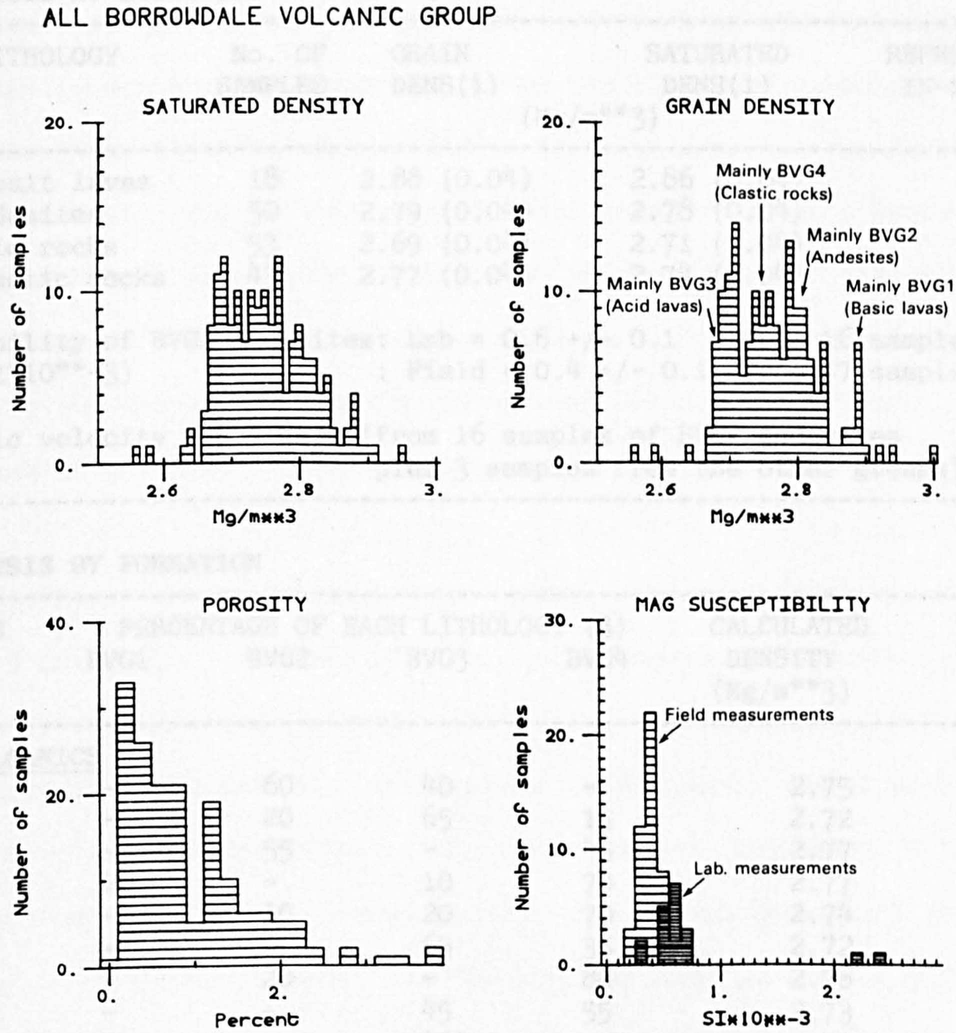
Figure 5.17 Statistics - Borrowdale Volcanic Group: BVG4 (clastic rocks)

reflects the compositional variation of this group. Where division into acid and basic varieties was possible, rocks derived from acid lavas fall into the low end of the range and those from basic lavas have higher densities (see listings in Appendix 7). On average the density of the reworked rocks is similar to (although slighlty less than) that of the BVG2 samples, reflecting a generally andesitic composition as anticipated.

Only 11 samples of tuff were analysed. Those positively identified as rhyodacitic or dacitic have a lower density than the others and the mean density is slightly lower than that of the reworked rocks (see listings in Appendix 7). The representative in-situ density of the group as a whole has been taken as 2.75 Mg/m^3, which is a compromise between the theoretical saturated density values (at 0.5% porosity) of 2.76 and 2.74 Mg/m^3 for volcaniclastic sandstones and tuffs respectively.

5.5.2 Formation densities

Statistics for all Borrowdale volcanic rocks are summarized in Figure 5.18 and the mean values listed in Table 5.6A. The histogram of grain densities shows four distinct populations corresponding to the four lithological groupings. The results give confidence that the basis of the analysis is sound, although as explained above, groups BVG2 and BVG4 cover a fairly wide range of compositions. On the basis of these data, densities were calculated for the formations identified in Figure 1.7 and the results are tabulated in Table 5.6B.



Number of samples = 166
Saturated density = 2.75 +/- 0.07 Mg/m**3
Grain density = 2.77 +/- 0.07 Mg/m**3
Porosity = 0.88 +/- 0.76 Percent
Theoretical sat dens at 0.2 % porosity = 2.76
Theoretical sat dens at 0.5 % porosity = 2.76
19 Lab suscept meas, Mean = 0.7 +/- 0.6 SI*10**-3
52 Fld suscept meas, Mean = 0.8 +/- 2.1 SI*10**-3
19 Sonic veloc meas, Mean = 6.4 +/- 0.1 Km/sec

Figure 5.18 Statistics - All Borrowdale Volcanic Group samples

Table 5.6 Summary of density, susceptibility and sonic velocity values for the Borrowdale Volcanic Group.

(A) ANALYSIS BY LITHOLOGY

LITH CODE	LITHOLOGY	No. OF SAMPLES	GRAIN DENS(1) (Mg/m**3)	SATURATED DENS(1) (Mg/m**3)	REPRESENTATIVE IN-SITU DENS
BVG1	Basalt lavas	18	2.88 (0.04)	2.86 (0.04)	2.88
BVG2	Andesites	50	2.79 (0.04)	2.78 (0.04)	2.78
BVG3	Acid rocks	53	2.69 (0.04)	2.71 (0.04)	2.70
BVG4	Clastic rocks	43	2.77 (0.04)	2.74 (0.04)	2.75

Susceptibility of BVG2 Andesites: Lab = 0.6 +/- 0.1 from 16 samples
(SI*10**-3) : Field = 0.4 +/- 0.1 from 47 samples

Mean sonic velocity = 6.4 km/s (from 16 samples of BVG2 Andesites plus 3 samples from the other groups)

(B) ANALYSIS BY FORMATION

FORMATION CODE (2)	PERCENTAGE OF EACH LITHOLOGY (3) BVG1	BVG2	BVG3	BVG4	CALCULATED DENSITY (Mg/m**3)
<u>UPPER VOLCANICS</u>					
G	-	60	40	-	2.75
K	-	20	65	15	2.72
N+W	-	55	-	45	2.77
P	20	-	10	70	2.77
SFT	-	10	20	70	2.74
DF	-	-	65	35	2.72
UL	-	20	-	80	2.76
B	-	-	45	55	2.73
AIR	-	-	100	-	2.70
<u>LOWER VOLCANICS</u>					
U	45	10	-	45	2.81
LB5	10	40	-	50	2.78
LB4	-	85	-	15	2.78
LB3	40	35	5	20	2.81
LB2	10	30	50	10	2.75
LB1	-	40	10	50	2.76

NOTES (1) Values given for grain and saturated densities are mean and standard deviation.

(2) Formations included under each code are shown in Figure 1.7.

(3) Information on the percentage of each lithology in each formation was provided by D. Millward (BGS).

The results illustrate the wide range of formation densities within the Borrowdale Volcanic Group. Of particular importance are the thick low-density sequences in the Upper BVG, such as the Airy's Bridge Formation, which are preserved within the Scafell, Haweswater and Ulpha synclines (see Figures 1.3 and 1.7). The high-density, mainly basic rocks lie at the base of the succession and occur at outcrop around the western granites and where they unconformably overlie the Skiddaw Group. Overall, the data provide a firm basis for detailed gravity modelling and for separating the effects of low density volcanic rocks from that of the granitic batholith.

Magnetic susceptibility and sonic velocity determinations (Table 5.6A) were carried out on an opportunistic rather than systematic basis and almost all refer to andesites (BVG2). Nevertheless, as rocks of intermediate composition, these might be expected to lie in the middle of the range for the Borrowdale Volcanic Group as a whole. The mean susceptibility of laboratory measurements is slightly higher than that of the Eskdale Granite (0.6 compared with 0.2 $SI*10^{-3}$). Basic rocks might be expected to record higher values and occasional samples give very high susceptibilities (see listings in Appendix 7). The mean sonic velocity value of 6.4 km/s is considerably higher than the average granite value. This could be significant as velocities above about 6.1 km/sec from deep seismic refraction data are usually assumed to represent continental (pre-Caledonian crystalline metamorphic) basement (eg. Bott et al. 1985).

5.6. THE SKIDDAW GROUP

The Skiddaw Group comprises a thick sequence of mudstone, siltstone and sandstone of Tremadoc, Arenig and Llanvirn age (see Chapter 1). Published density values make no reference to lithology or formation. Bott (1974) reported a mean saturated density of 2.77 Mg/m^3 (grain density 2.79 Mg/m^3) based on 53 samples from 4 localities mainly in the central part of the inlier. The present author (Lee 1984a and Table 4.1) reported a mean saturated density of 2.80 Mg/m^3 (grain density 2.83 Mg/m^3) based on samples from 7 localities mainly in the eastern part of the inlier. The objective of the present study was to examine density variations within the Skiddaw Group, in particular between the mudstone and sandstone lithologies of the Hope Beck, Loweswater and Kirk Stile Formations. Samples were provided by the BGS geologists (see below) from some 80 localities and classified according to Jackson's (1978) lithology (at the time of collecting the samples, Cooper and Webb had not proposed their new stratigraphy).

The analysis was carried out in close collaboration with A.H. Cooper (BGS) who advised on the proportion of sandstone and mudstone in each formation and provided many of the rock samples. Other samples were provided by P.M. Allen and D.C. Cooper (BGS). All samples were selected to be 'typical' of their lithology and/or formation. The analyses are discussed in terms of lithology in Section 5.6.1 and in terms of formation in Section 5.6.2. Complete listings corresponding to each set of histograms are given in Appendix 7 (Section A7.3).

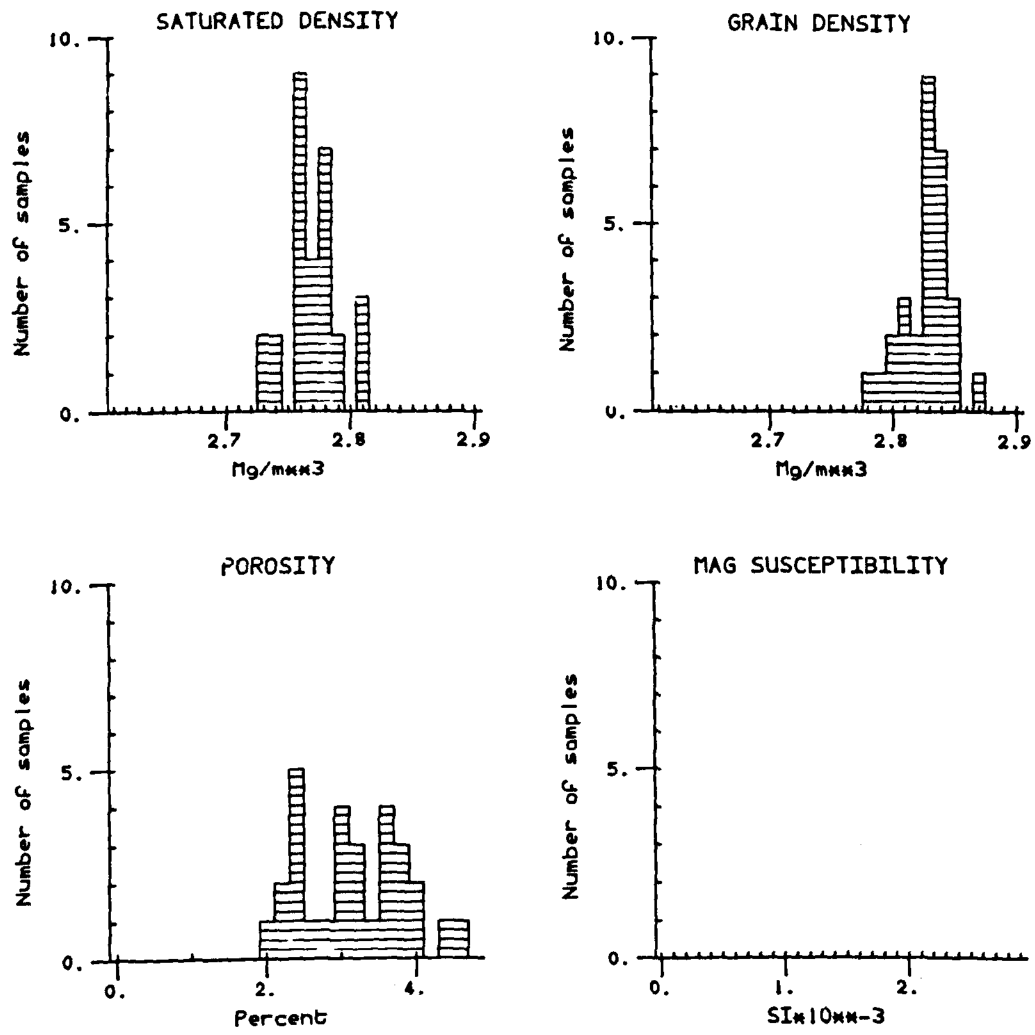
5.5.1 Analysis by lithology

Statistics for all mudstone and siltstone samples from the Hope Beck and Kirk Stile formations (including unspecified samples from both formations) are given in Figure 5.19. Separate calculations for each formation are given in Appendix 7 (Section A7.3), together with the statistics for the 4 samples of mudstones from the Loweswater Formation.

Grain density values mostly fall in the range 2.78 to 2.85 Mg/m^3. Means for the Hope Beck, Kirk Stile and undivided samples are very similar (2.82, 2.83 and 2.83 Mg/m^3 respectively) while that for the Loweswater Formation is lower (2.79 Mg/m^3) but is based on only four samples. The histogram for all samples from the Hope Beck and Kirk Stile formations (Figure 5.19) suggests the presence of two populations, the lower density group presumably representing samples which tend towards a more sandstone/ greywacke composition. The few samples from the Kirk Stile Formation in the eastern part of the inlier have grain density values towards the upper end of the mudstone/siltstone range (see listings in Appendix 7).

Porosity values for the mudstone and siltstone samples are generally high, mostly in the range 2% to 4%. This is considered to be partly due to separation of the slaty layers, especially where samples are slightly weathered. In-situ porosity values are not easy to estimate. It is difficult to justify adopting a value much lower than the bottom end of the measured range but porosities may be considerably lower at depth where the rocks are under pressure. If a porosity value 2% is assumed, the in-situ saturated density of mudstone/siltstone samples is 2.79 Mg/m^3, based on a mean grain density of 2.83 Mg/m^3

SKIDDAW GP - MUD/SLT (HOPE BK + KIRK ST + UNSPEC)



Number of samples = 29
Saturated density = 2.77 +/- 0.02 Mg/m**3
Grain density = 2.83 +/- 0.02 Mg/m**3
Porosity = 3.17 +/- 0.67 Percent
Theoretical sat dens at 1.0 % porosity = 2.81
Theoretical sat dens at 2.0 % porosity = 2.79

Figure 5.19 Statistics - All unaltered mudstone and siltstone in the Hope Beck and Kirk Stile formations (including unspecified samples from these formations).

(Figure 5.19). The equivalent value assuming a porosity of 1% is 2.81 Mg/m^3.

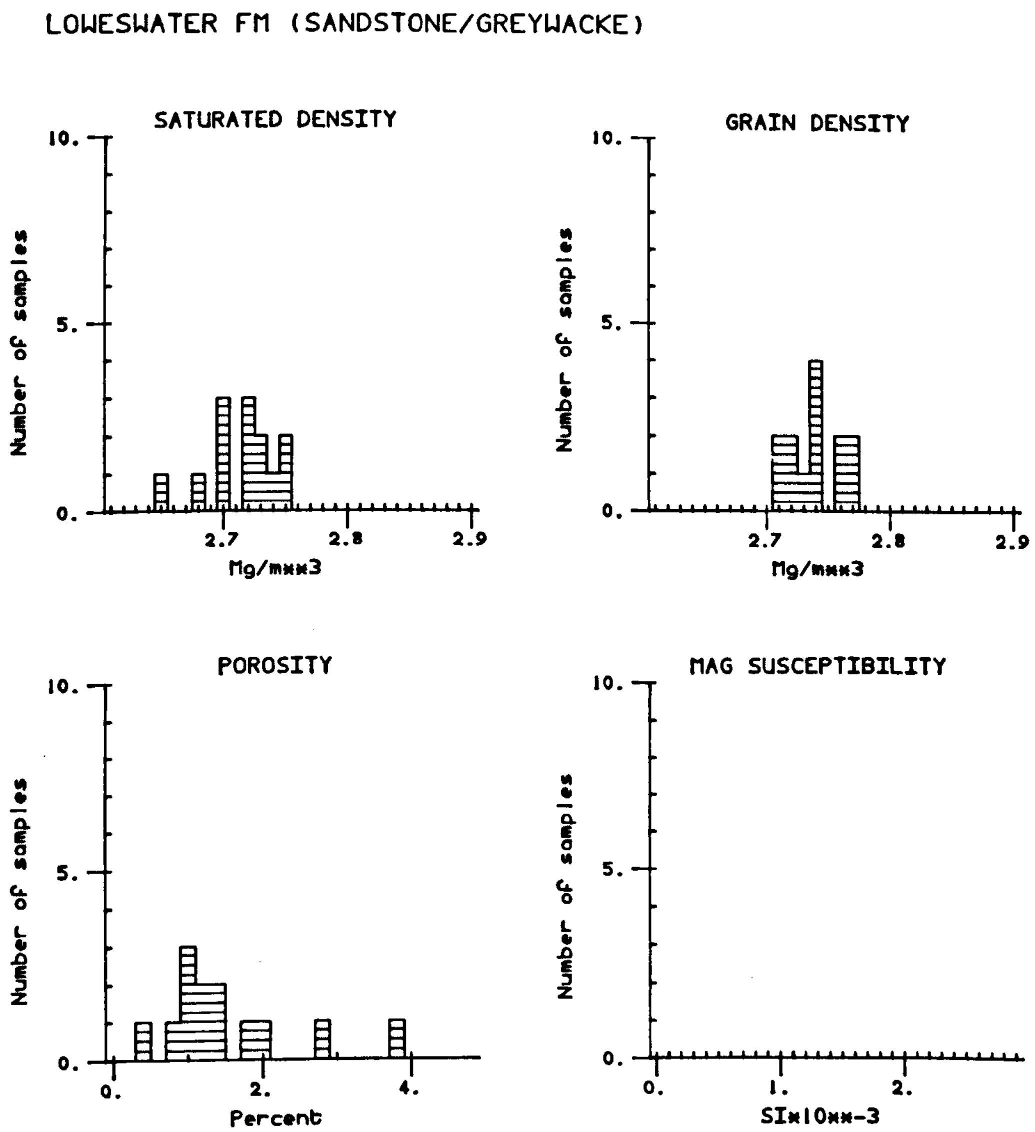
Only the Loweswater Formation contains a significant proportion of sandstone and greywacke. Thirteen samples gave a mean grain density of 2.74 Mg/m^3 (Figure 5.20) which is considerably lower than the mudstone/siltstone mean. Porosities are also generally lower, a value between 0.5% and 1% is probably representative of the in-situ porosity. Theoretical saturated densities based on these values are 2.73 and 2.72 Mg/m^3 respectively.

Within the Loweswater Formation, sedimentary structures arranged in Bouma sequences (Bouma 1962) are recognized (ie. sandstone to mudstone cyclic sedimentation). Five samples from a single cycle were analysed to examine small-scale density variations with composition. The results are given in Table 5.7 (see Appendix 7 for details of each sample). Grain density values increase as the particle size decreases throughout the cycle and porosity values for the mudstone (slate) samples are high. This is in line with what might be expected from the general results (above) but it is interesting to note that such variations occur also on the small scale.

Table 5.7 Values across a single Bouma sequence.

UNIT	COMPOSITION	POROSITY (%)	SAT DENS (Mg/m**3)	GRAIN DENS (Mg/m**3)
A	coarse-grained sandstone	0.8	2.70	2.71
B	uniform medium-grained sandstone	1.2	2.70	2.72
C	sandstone with convoluted bedding	2.8	2.70	2.74
D	silty mudstone with siliceous laminae	3.7	2.73	2.79
E	dark grey silty mudstone	4.8	2.72	2.80

NOTE: Samples provided by D.C. Cooper.



Number of samples = 13
Saturated density = 2.71 +/- 0.03 Mg/m**3
Grain density = 2.74 +/- 0.02 Mg/m**3
Porosity = 1.50 +/- 0.93 Percent
Theoretical sat dens at 0.5 % porosity = 2.73
Theoretical sat dens at 1.0 % porosity = 2.72

Figure 5.20 Statistics - Sandstone and greywacke from the Loweswater Formation.

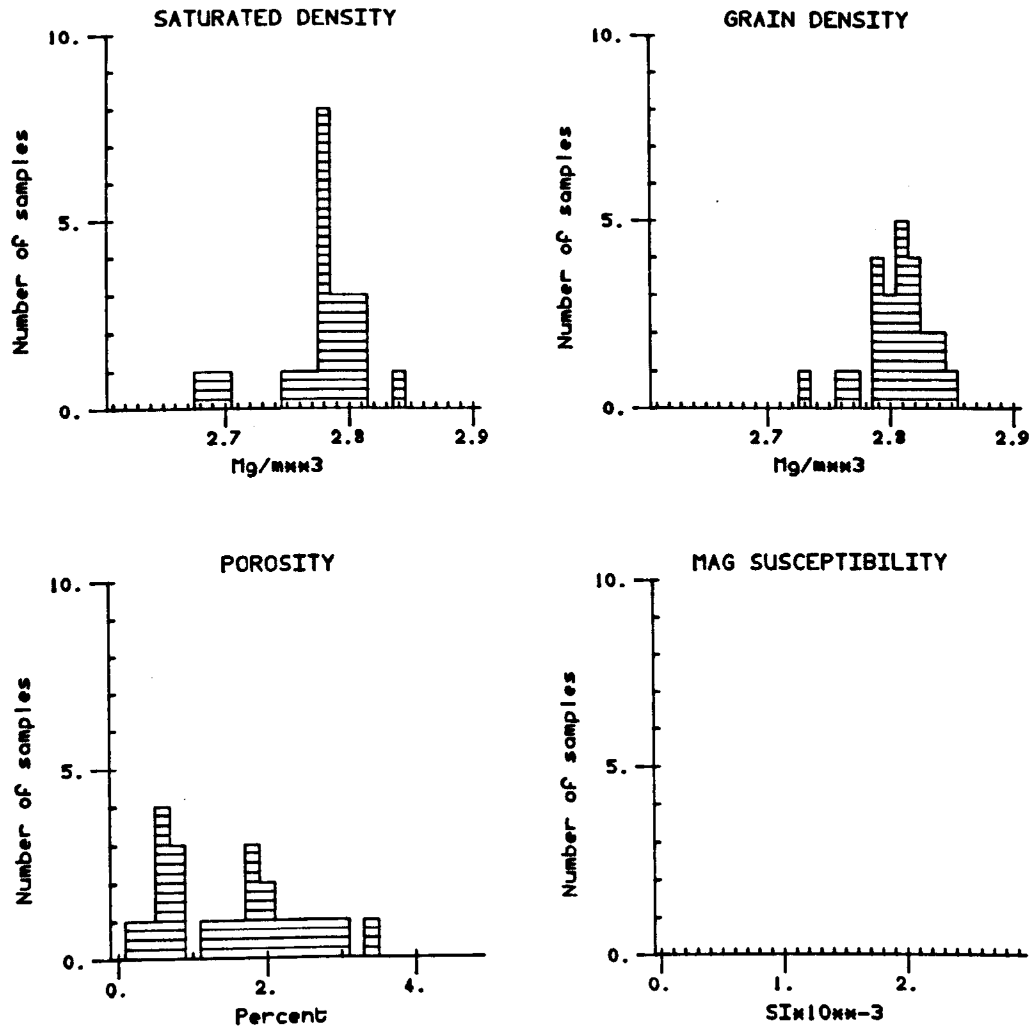
Statistics for 24 samples of bleached mudstone and siltstone from within the Crummock aureole are given in Figure 5.21. Grain densities are marginally lower, and saturated densities higher, than for normal mudstones and siltstones, the latter effect due to the lower porosities of these indurated rocks. Samples collected along a traverse which crosses the contact zone (Figure 5.22) also illustrates this point. Overall, the data suggest that in-situ saturated density values within the aureole are similar to those outside.

Five samples of hornfelsed mudstone from the Black Combe inlier and close to the Eskdale and Ennerdale intrusions were acquired during the course of the gravity surveys. The statistics (Figure 5.23) show grain densities at the high end of the mudstone/siltstone range and attention is also drawn to the particularly high porosity values of the samples from Black Combe (see listing in Appendix 7 for details). The results for all Skiddaw Group samples are summarised in Figure 5.24.

5.6.2 Formation and bulk densities

Table 5.8 shows calculated densities for the main Skiddaw Group formations and estimated bulk densities for the whole sequence. The calculations are based on estimates of the proportion of each lithology in each formation provided by A.H. Cooper (BGS). The density values adopted for gravity modelling depend on which in-situ porosity value is assumed and, to a certain extent, the objective of the interpretation. A density of 2.78 Mg/m^3 is probably an appropriate background value for the group as a whole at depth (for large scale modelling), but values as high as 2.81 Mg/m^3 may be more representative for some areas where mudstone and siltstone lithologies predominate.

SKIDDAW GROUP (IN CRUMMOCK AUREOLE)



Number of samples = 24
Saturated density = 2.78 +/- 0.04 Mg/m**3
Grain density = 2.81 +/- 0.03 Mg/m**3
Porosity = 1.67 +/- 1.17 Percent
Theoretical sat dens at 0.5 % porosity = 2.80
Theoretical sat dens at 1.0 % porosity = 2.79

Figure 5.21 Statistics - Mudstone and siltstone from the Crummock aureole.

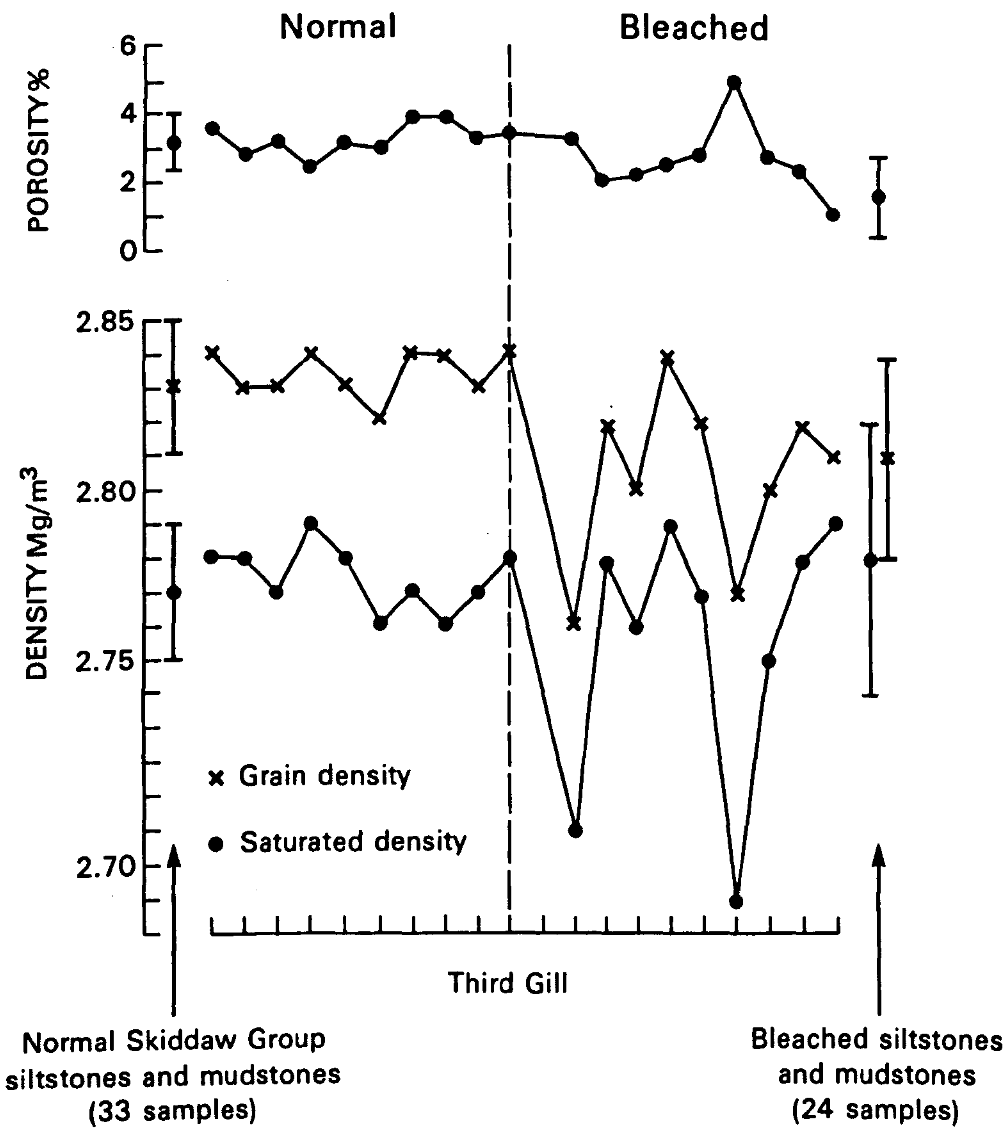
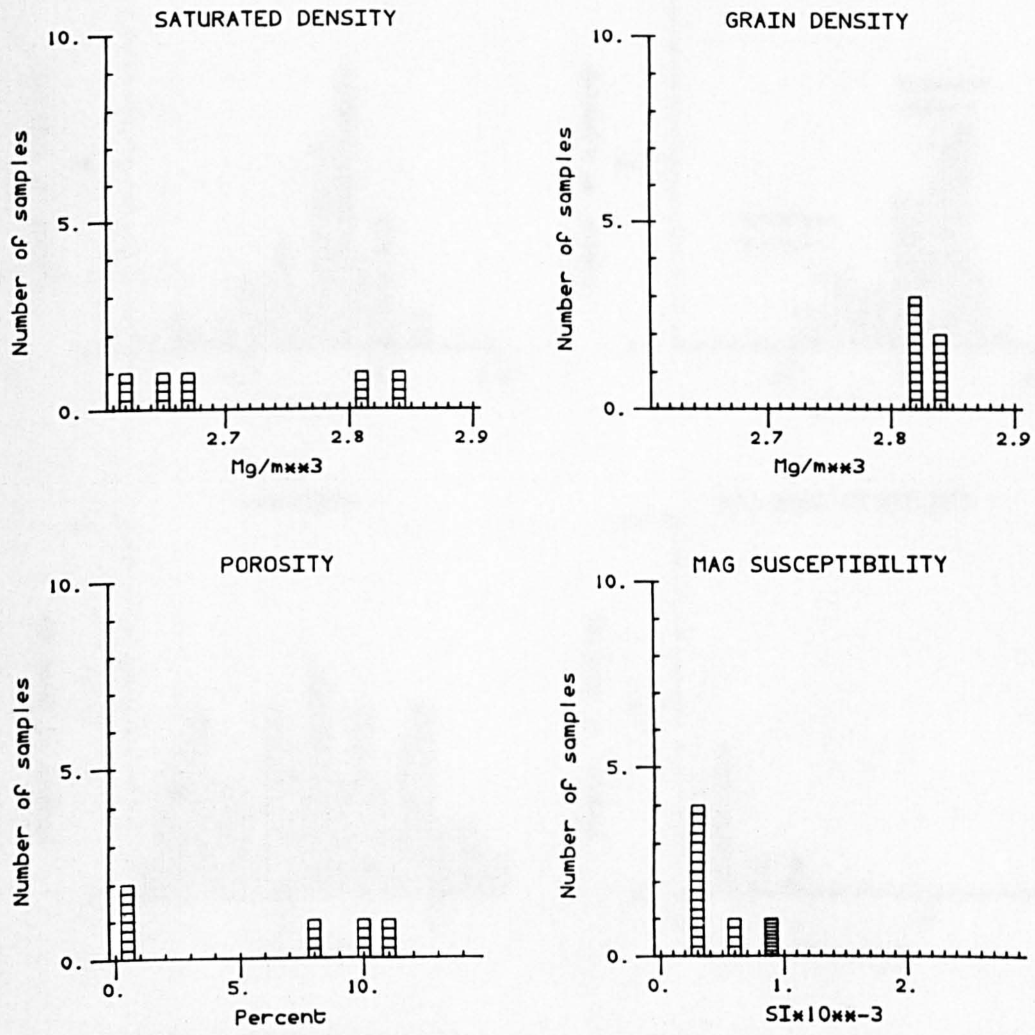


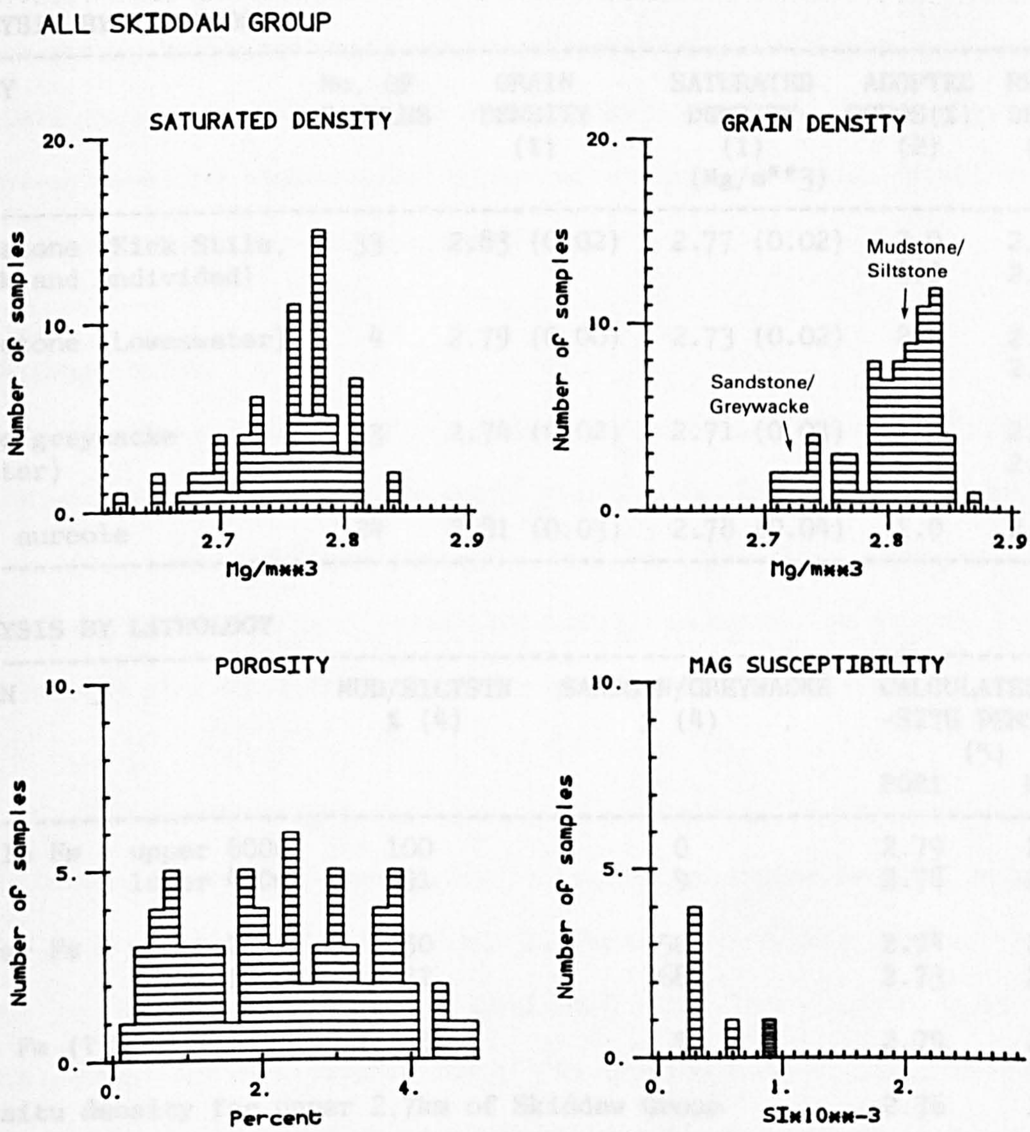
Figure 5.22 Density traverse across the margin of the Crummock aureole.

SKIDDAW GROUP - HORNFELSED ROCKS EXCL CRUMMOCK



Number of samples = 5
Saturated density = 2.72 +/- 0.10 Mg/m**3
Grain density = 2.83 +/- 0.01 Mg/m**3
Porosity = 6.10 +/- 5.17 Percent
Theoretical sat dens at 1.0 % porosity = 2.81
Theoretical sat dens at 2.0 % porosity = 2.79
1 Lab suscept meas, Mean = 0.9 +/- 0.0 SI*10**-3
5 Fld suscept meas, Mean = 0.4 +/- 0.1 SI*10**-3
1 Sonic veloc meas, Mean = 5.9 +/- 0.0 Km/sec

Figure 5.23 Statistics - Hornfelsed Skiddaw Group rocks.



Number of samples = 77
Saturated density = 2.76 +/- 0.04 Mg/m**3
Grain density = 2.80 +/- 0.04 Mg/m**3
Porosity = 2.71 +/- 2.00 Percent
Theoretical sat dens at 1.0 % porosity = 2.79
Theoretical sat dens at 2.0 % porosity = 2.77
1 Lab suscept meas, Mean = 0.9 +/- 0.0 SI*10**-3
5 Fld suscept meas, Mean = 0.4 +/- 0.1 SI*10**-3
1 Sonic veloc meas, Mean = 5.9 +/- 0.0 Km/sec

Figure 5.24 **Statistics - All Skiddaw Group rocks.**

Table 5.8 Summary of density data for the Skiddaw Group and calculated density values for specific formations.

(A) ANALYSIS BY LITHOLOGY

LITHOLOGY	No. OF SAMPLES	GRAIN DENSITY (1)	SATURATED DENSITY (1) (Mg/m**3)	ADOPTED POROS(%) (2)	REPRES DENSITY (3)
Mud/siltstone (Kirk Stile, Hope Beck and undivided)	33	2.83 (0.02)	2.77 (0.02)	2.0 1.0	2.79 2.81
Mud/siltstone (Loweswater)	4	2.79 (0.00)	2.73 (0.02)	2.0 1.0	2.76 2.77
Sandstone/greywacke (Loweswater)	13	2.74 (0.02)	2.71 (0.03)	1.0 0.5	2.72 2.73
Crummock aureole	24	2.81 (0.03)	2.78 (0.04)	1.0	2.79

(B) ANALYSIS BY LITHOLOGY

FORMATION	MUD/SILTSTN % (4)	SANDSTN/GREYWACKE % (4)	CALCULATED IN-SITU DENSITY (5) POR1	POR2
Kirk Stile Fm - upper 600m	100	0	2.79	2.81
lower 400m	91	9	2.78	2.80
Loweswater Fm - upper 200m	50	50	2.74	2.75
lower 1000m	32	68	2.73	2.74
Hopebeck Fm (? 500m +)	95	5	2.79	2.81
Bulk in-situ density for upper 2.7km of Skiddaw Group			2.76	2.78

NOTES: (1) Values given for grain and saturated densities are mean and standard deviation.

(2) Estimated in-situ porosity.

(3) Representative in-situ density calulated from the grain density using the indicated porosity value.

(4) Information on the percentage of each lithology in each formation was provided by A.H. Cooper (BGS).

(5) POR1 indicates densities calculated assuming mudstone and sandstone porosities of 2% and 1% respectively. POR2 indicates densities calculated assuming mudstone and sandstone porosities of 1% and 0.5% respectively.

The important point to note is that the Loweswater Formation is 0.04 to 0.06 Mg/m^3 less dense than the Kirk Stile and Hope Beck formations. In terms of the new stratigraphy proposed by Cooper and Webb (pers.comm.), the 'sandstone lithologies' are 0.04 to 0.06 Mg/m^3 less dense than the mudstone/siltstone pile (note, however, that the Watch Hill Formation was not sampled).

5.7. SILURIAN ROCKS

Upper Ordovician and Silurian rocks (classified by Moseley (1984) as the Windermere Group) unconformably overlie the Borrowdale Volcanic Group in the southern Lake District (Figure 1.3). The sequence is approximately 5km thick and comprises mainly mudstone, siltstone and greywacke. The principal formations are described in Table 1.1.

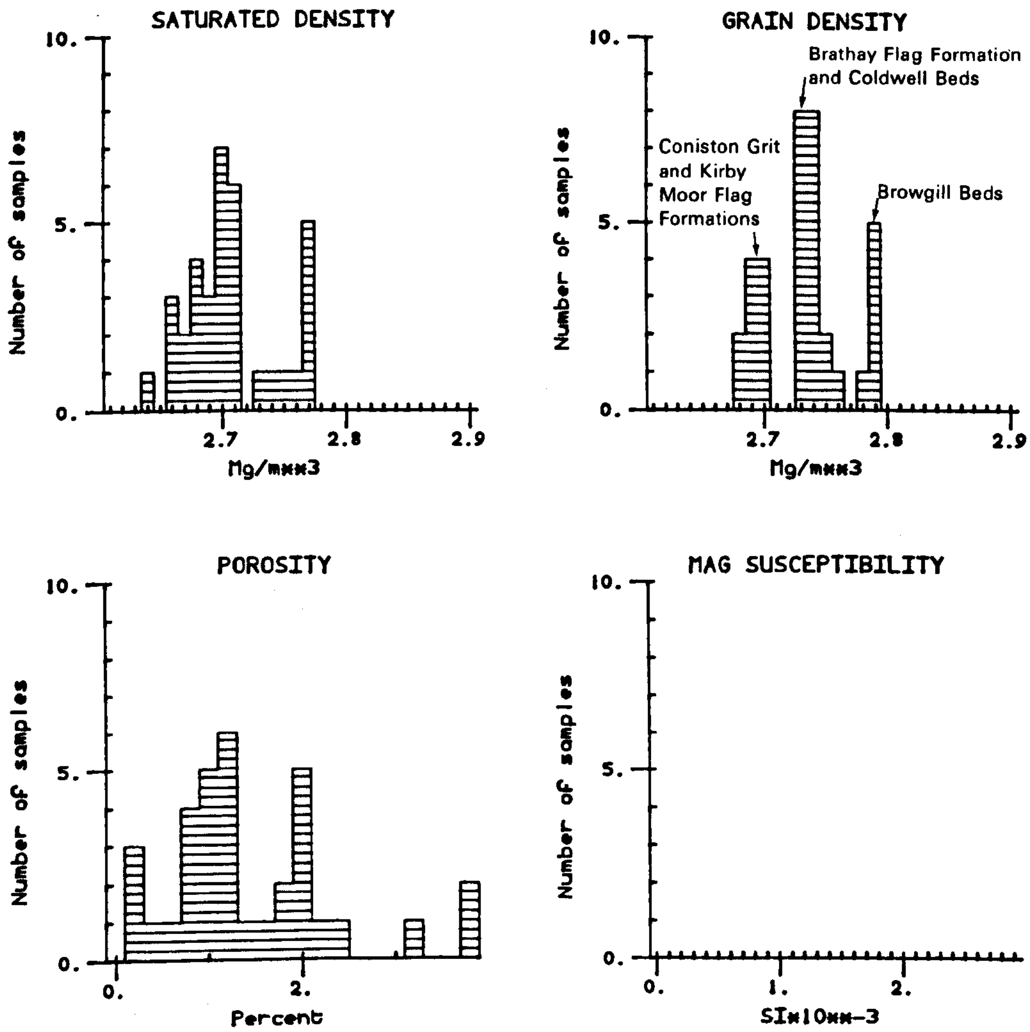
Although previous gravity interpretations (eg. Bott 1974 and Chapter 4 of this thesis) have tended to assume a single density value for the whole pile, some information on density variations within the sequence is discernible from the published data. Bott (1974) quoted separate values for the Brathay Flags (41 samples from 2 localities), Bannisdale Slates (21 samples from 1 locality) and Kirby Moor Flags (20 samples from 1 locality). The present author (Lee 1984a) published additional values for the Bannisdale Slates (10 localities) and a few determinations on Coniston Grit, Brathay Flag and Coldwell Bed samples (Chapter 4, Table 4.1).

In order to investigate density variations in more detail, determinations were carried out on a small number of samples from each of the principal formations (excluding the Bannisdale Slates which were already well represented). As with the Skiddaw Group, BGS were in the process of re-mapping the area and representative samples had been collected by the geologists. 'Typical' samples from the Browgill Beds, Middle and Upper Coldwell Beds, Brathay Flags, Coniston Grits and Kirby Moor Flags were provided by D. Lawrence (BGS Newcastle). The combined statistics for all samples from these formations are shown in Figure 5.25 and separate listings for each formation are given in Appendix 7 (Section A7.4). It should be noted that each set of 'typical' samples was collected from a single location.

Grain densities generally decrease towards the top of the sequence. Values for the Browgill Beds are similar to the average for the Skiddaw Group; porosity values are well clustered around 1% and the mean saturated density of 2.77 Mg/m^3 is probably representative of the in-situ density. The Brathay Flags and Coldwell Beds have lower grain density values. The mean porosity for the Brathay Flags is slightly less than 1% and the mean saturated density of 2.73 Mg/m^3 is considered representative of the in-situ density of these samples. Porosity values for the Middle and Upper Coldwell Beds are slightly higher; the best value for the in-situ saturated density is probably given by the upper end of the range of saturated density values (ie. 2.71 Mg/m^3).

The density of the Coniston Grits is, as expected of greywackes, lower than that of the preceding formations. Porosities, however, are particularly low and the mean saturated density of 2.69 Mg/m^3 is considered representative of the in-situ density. The Kirby Moor Flags have the same grain density as the Coniston Grits but slightly higher porosity. The mean saturated density is 2.67 Mg/m^3.

ALL SILURIAN



Number of samples = 35
Saturated density = 2.71 +/- 0.04 Mg/m**3
Grain density = 2.73 +/- 0.03 Mg/m**3
Porosity = 1.47 +/- 1.01 Percent
Theoretical sat dens at 0.5 % porosity = 2.72
Theoretical sat dens at 1.0 % porosity = 2.72

Figure 5.25 Statistics - All Silurian samples.

Table 5.9 summarizes density values for Silurian rocks from all sources and gives what are considered to be the most appropriate in-situ density values for gravity modelling. For certain formations, data from the different sources do not agree exactly and it is not certain whether the previously published data are fully representative. In these cases some subjective judgement has been used to arrive at an appropriate in-situ value. The Kirby Moor Flags, where grain density values are significantly different, are the most problematical; Bott's (1974) saturated density value has been chosen as a reasonable compromise.

TABLE 5.9 Summary of density data for Silurian rocks.

FORMATION	SOURCE	No. OF LOCS	No. OF SAMPLES	SAT DENS	GRAIN DENS (Mg/m**3)	IN-SITU DENSITY
Kirby Moor Flag Fm	B	1	20	2.69	2.74	
	A	1	4	2.67	2.69	
		Suggested representative value =				2.69
Bannisdale Slate Fm	B	1	21	2.72	2.73	
	C	10	10	2.69	2.74	
		Suggested representative value =				2.72
Coniston Grit Fm	C	1	2	2.69	2.72	
	A	1	5	2.69	2.69	
		Suggested representative value =				2.69
U+M Coldwell Beds	A	2	15	2.69	2.73	
		Suggested representative value =				2.71
Brathay Flag Fm	B	2	41	2.74	2.77	
	A	1	5	2.73	2.74	
		Suggested representative value =				2.74
Browgill Beds	A	1	6	2.77	2.79	
		Suggested representative value =				2.77
Undivided Silurian (based on thicknesses in Table 1.1) =						2.71
Buried Silurian (ie. assuming lower porosity values) =						2.72

REFERENCES: A = This chapter, B = Bott (1974), C = Lee 1984a (and Table 4.1)

5.8. SUMMARY OF DENSITY CONTRASTS FOR LOWER PALAEOZOIC ROCKS

In-situ density values for the principal lithologies and formations in the Lake District are summarized in Figure 5.26. The analysis has identified significant density variations in both the Skiddaw and Borrowdale Volcanic groups which should be taken into account during gravity modelling. The density of each of the granites which make up the composite batholith is better defined than previously. The data show no evidence for systematic density variations within each intrusion.

There is still considerable scope for further work - densities within the eastern part of the Skiddaw Group outcrop, the Ullswater, Bampton and Black Combe inliers, and within the aureole of the Skiddaw Granite are not defined by the present dataset. The same applies to the Eycott Volcanic Group, where density variations could be important in interpreting the form of the northern margin of the Lake District batholith. It is anticipated that detailed studies of these areas will be carried out in parallel with the on-going BGS re-mapping programme.

5.9 CARBONIFEROUS AND PERMO-TRIASSIC ROCKS

Several density determinations for Carboniferous and Permo-Triassic rocks have been reported in the literature (see Section 4.2 and Table 4.2) but it often difficult to estimate bulk, in-situ densities from these values. Densities derived from formation density logs in deep boreholes are considered to provide more representative bulk values for modelling purposes.

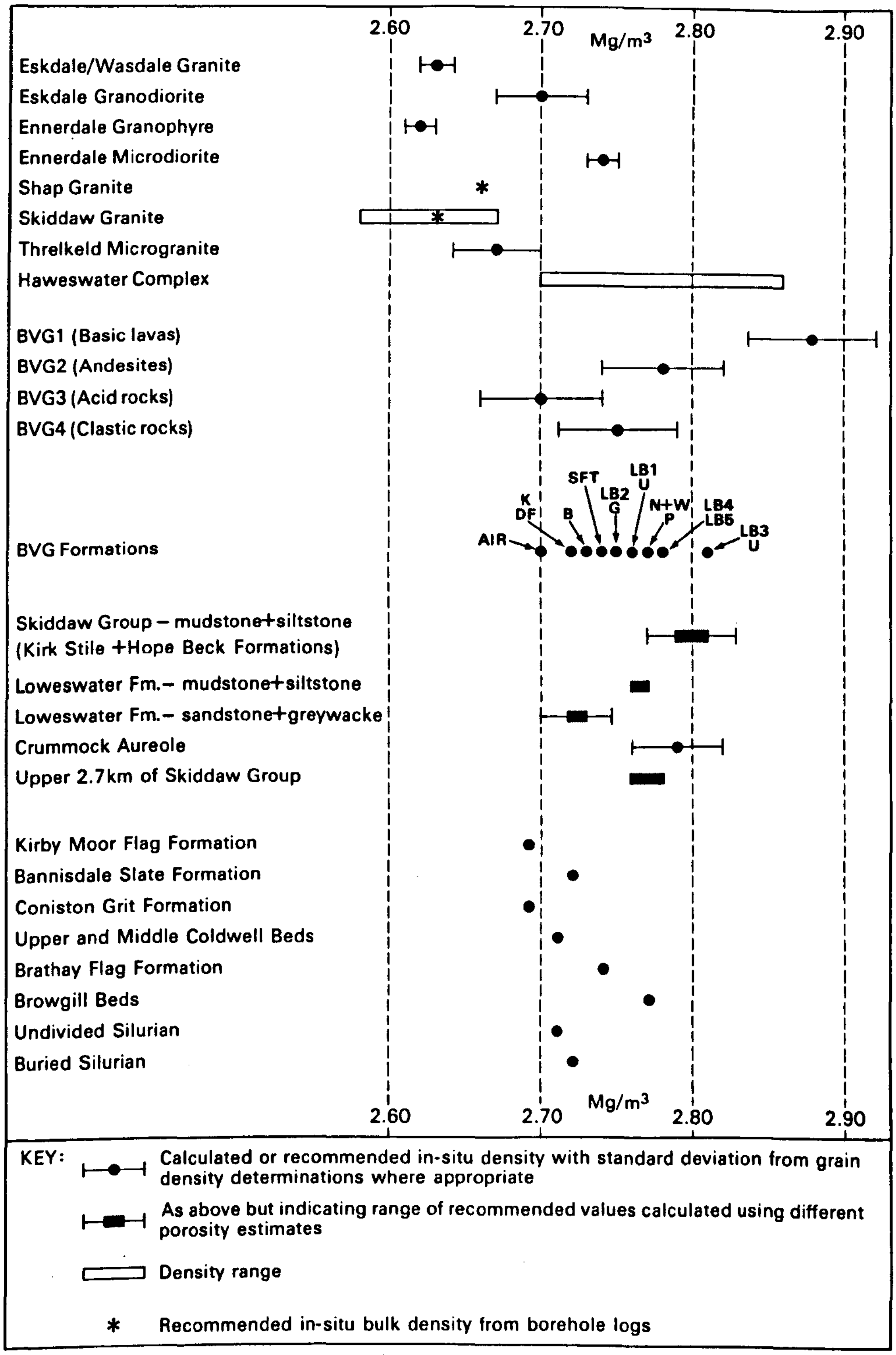


Figure 5.26 Summary of Lake District density data.

Bott & Masson Smith (1957) quoted values for Dinantian limestone, sandstone and shale from north-east England of 2.68, 2.56 and 2.42 Mg/m^3 respectively, but the bulk density of the Dinantian sequence depends on the relative proportions of these rock types in the sedimentary pile. Bott (1974) estimated the density of a typical Yoredale sequence as 2.60 Mg/m^3 but recent borehole data suggests that this is not typical of the Lower Carboniferous. Kimbell et al. (1989) quote an average of 2.66 Mg/m^3 for the Middle and Upper Border groups and the Lower and Upper Liddesdale groups (including the Whin Sill and Canbeck Beds, see Figure 1.9), and 2.70 Mg/m^3 for the Lower Border Group (excluding the Cambeck Beds) based on confidential borehole logs from the Northumberland Trough.

Data from the same source (Kimbell et al. 1989) give an average of 2.50 Mg/m^3 for the Coal Measures and Stainmore Group. These compare with values derived by Smith et al. (1980) from the Kirkham borehole and two boreholes in the Irish Sea of 2.53 Mg/m^3 for the Namurian (i.e. Stainmore Group) and 2.60 Mg/m^3 for the Westphalian (Coal Measures). The latter value seems rather high when compared with that of Kimbell et al. (1989) and another estimate based on surface samples of 2.47 Mg/m^3 reported by Bott & Masson Smith (1957).

Density values from surface samples and borehole logs are also available for the Permian and Triassic sequences around the Lake District. Bott (1974 and 1978) quoted saturated density values of 2.42 Mg/m^3 for the Penrith sandstone, 2.46 Mg/m^3 for the St Bees Shale and 2.22 Mg/m^3 for the St Bees Sandstone, and he adopted values of 2.23 and 2.43 Mg/m^3 for the St Bees Beds and Penrith Sandstone respectively for his gravity interpretation of the Vale of Eden. Smith et al. (1980)

estimated a value of 2.48 Mg/m^3 for the bulk, in-situ density of the Permo-Triassic succession based on density logs from the Prees, Kirkham and two Irish Sea boreholes. The present author (Lee 1984a) estimated the density of the Permo-Triassic succession in the Irish Sea as 2.43 Mg/m^3 and Carruthers (1980) quoted a value of 2.45 Mg/m^3 for the Permian sequence in the Silloth No. 1 borehole in the Solway Basin [NY 12306 54849].

The Silloth No. 1 borehole extends to a depth of 1342m and proved a complete Permo-Triassic succession unconformably overlying rocks of presumed Lower Carboniferous age (Figure 5.27). Formation density logs are only available for the lower 600m but logs from a second shallow borehole drilled nearby (Silloth No. 2 [NY 12410 54380]) provide information for the upper 300m of the sequence. Together these boreholes provide the best available density data for the Permo-Triassic seccession adjacent to the Lake District. Neither of the density logs is available in machine readable form but the original paper records have been reanalysed to give estimates of in-situ values over most of the sequence.

The results (Figure 5.28) show that the density increases from about 2.40 to 2.60 Mg/m^3 over the upper 300m of the sequence and an average value of 2.50 Mg/m^3 is considered appropriate for the Stanwix Shales. The lower part of the St Bees Sandstone has a mean density of around 2.56 Mg/m^3, increasing to 2.66 Mg/m^3 in the St Bees Shale. The underlying Penrith Sandstone is less dense at around 2.46 Mg/m^3. Density logs are not available for the Kirklinton Sandstone and the upper part of the St Bees Sandstone. The geological, gamma and sonic

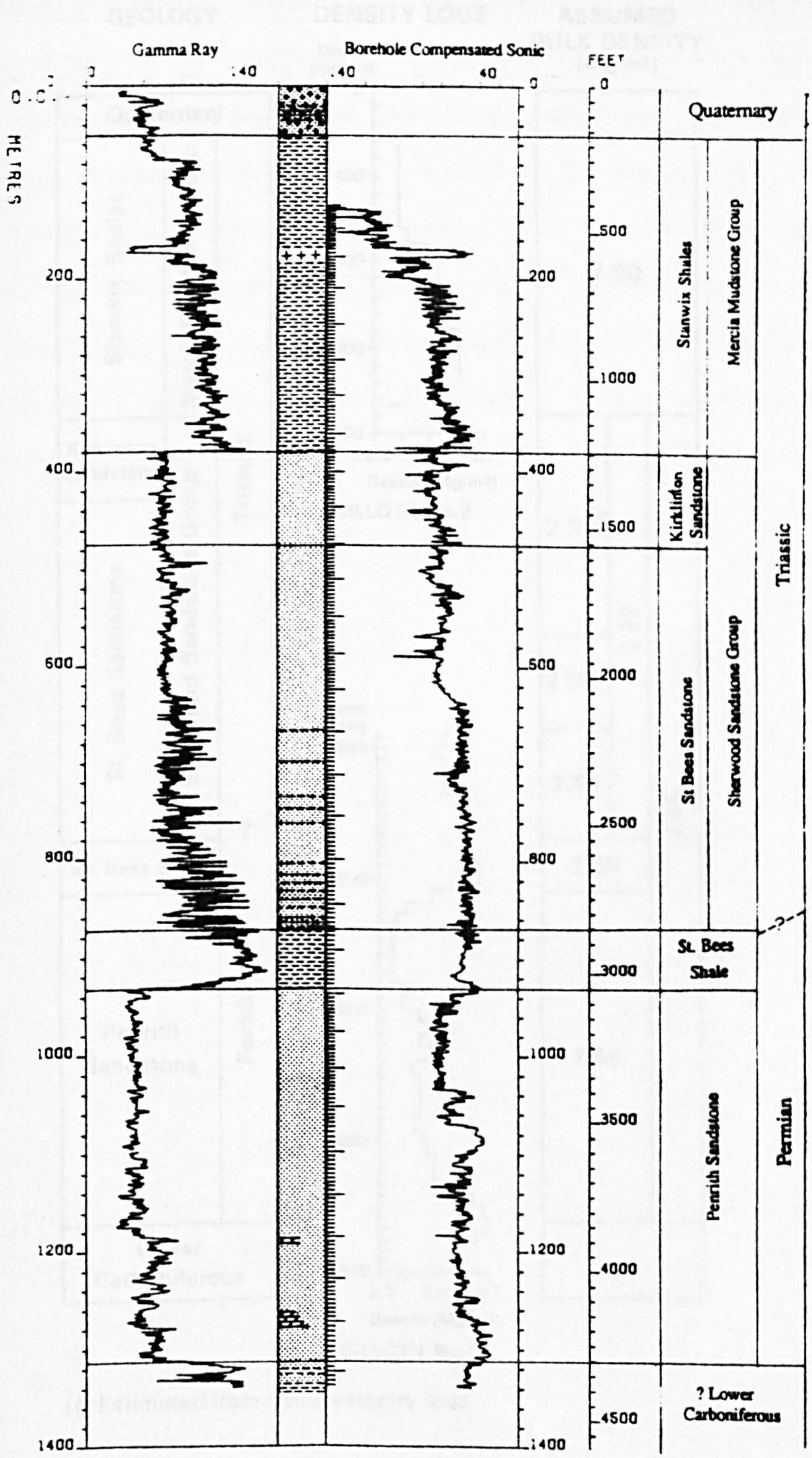


Figure 5.27 Geophysical logs and summary geology from the Silloth borehole (Abbott 1987, Figure 3).

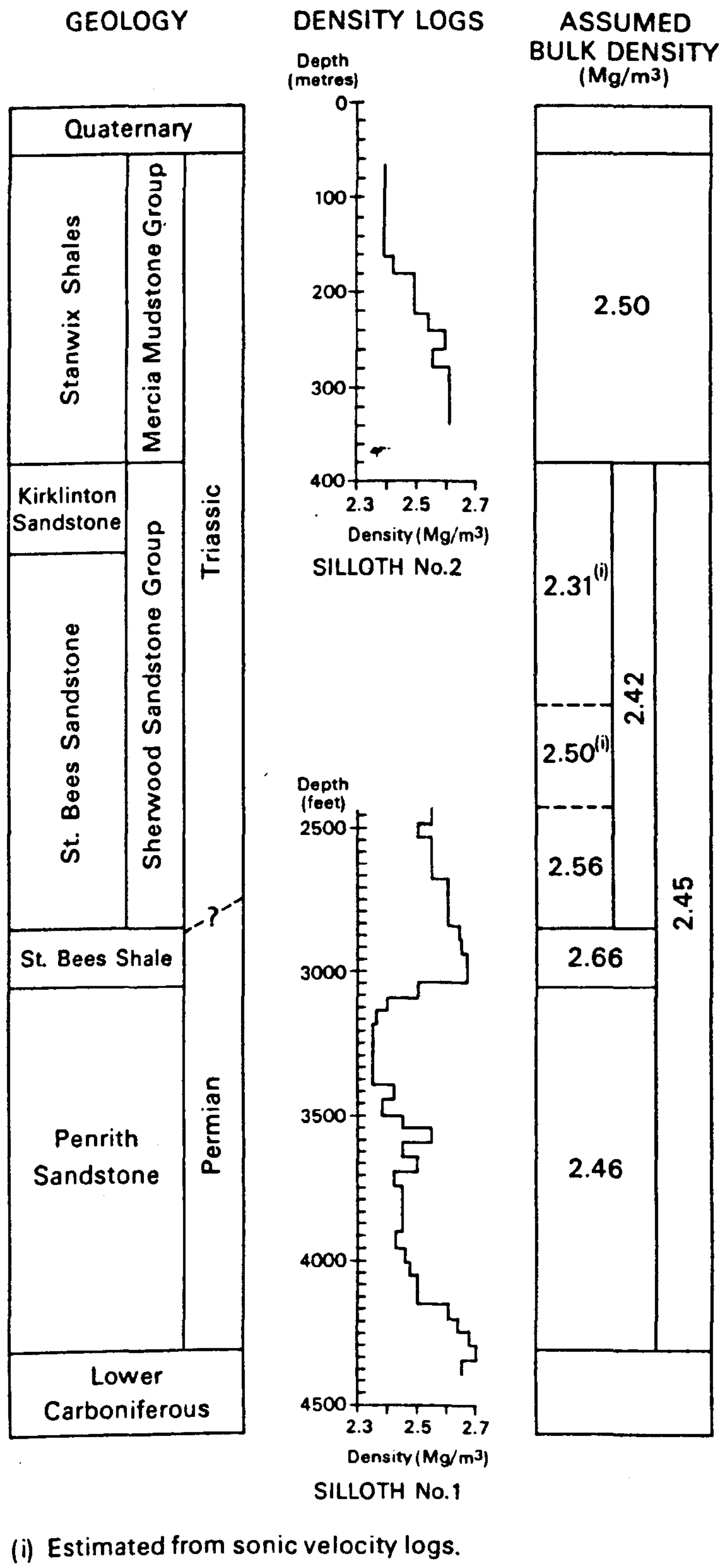


Figure 5.28 Analysis of density logs from the Silloth borehoes.

logs shown on Figure 5.27 indicate an increase in shale content in the St Bees Sandstone below about 640m. Density values have been estimated over the missing interval from the sonic velocity log using the relationship between density and velocity in sandstone (MKL in conjunction with G.S. Kimbell, BGS). The results suggest that the less shaly parts of the Kirklinton and upper St Bees Sandstone formations probably have an in-situ density of around 2.31 Mg/m^3 and the interval 640 - 740 m has a density of around 2.5 Mg/m^3. These values have been adopted in calculating the averages shown on Figure 5.28.

CHAPTER 6

STRUCTURAL ANALYSIS OF GRAVITY AND MAGNETIC FIELDS USING IMAGE PROCESSING TECHNIQUES

6.1 INTRODUCTION

As gravity and magnetic datasets in digital form have become increasingly available, image processing techniques, originally developed for analysing remotely sensed data, have been applied to the analysis of the potential fields. This has led to the recognition that traditional methods of presentation (i.e. contour maps) often filter out much of the information content of the data related to geological structure and trend.

Grey-scale shaded-relief and colour-shaded images have proved particularly effective forms of presentation for potential field data. They contain information on both anomaly amplitude (colour) and anomaly gradient (relief), and exploit the human visual system's inherent ability to interpret intensity and textural information (Drury & Walker 1987). The latter is particularly important as anomaly gradients are directly related to the depth of burial of the causative structures. Shaded-relief presentations, which treat the field as topography illuminated from a particular direction, have the additional advantage of enhancing features that trend roughly perpendicular to the direction of illumination. This has the effect of enhancing subtle, but often important lineaments which were not apparent on the original contour maps.

In addition to their image enhancement capabilities, image processing systems offer a means by which different datasets can be compared and jointly analysed in terms of common features and statistical correlations. This has proved particularly effective in the field of mineral exploration where targeting criteria and mineralization models can be developed by recognizing correlations between particular geological, geophysical and geochemical signatures (e.g. Plant et al. 1988).

The gravity and magnetic data from the Lake District have been analysed using the I^2S image processing facility at BGS Keyworth. The objective was to evaluate and further develop techniques for enhancing subtle anomalies and structural trends related to both the local geological structure and plate-tectonic evolution of the area. The main part of the study was concerned with the detailed analysis of a 110 x 110 km area covering the Lake District itself (the area covered by Figures 1.2, 2.3 and 2.7). However, images of the northern England region and the whole of Britain south of the Highland Boundary Fault were prepared to help set the Lake District in its plate-tectonic context.

6.2 DATA PREPARATION AND GRIDDING

Digital images are based on a raster format in which each pixel represents the value of a particular grid cell. In order to generate an image, therefore, irregularly-spaced data must first be interpolated onto a regular grid. The quality of the final image is critically dependent on the quality of the gridding algorithm, especially where the data are unevenly-spaced or arranged along lines as is the case for the aeromagnetic data. The I^2S image processing system can display images up to 512 x 512 pixels. In order to produce a reasonably sized image of the 110 x 110 km Lake District study area, therefore, a 0.25 km grid interval is required.

Traditional 'radial-search' gridding techniques tend to produce poor results for line-based data or if the gridding interval is very much less than the average data spacing. Initially, the best results were obtained by using a 'radial-search' gridding algorithm to interpolate onto a 1 km grid and then expanding this by a factor of four using the 'bilinear zoom' function on the image processer. Although quite well-behaved in most areas, these grids still tended to exhibit the 'blockiness' characteristic of radial-search techniques in regions of sparse data coverage (e.g. offshore).

In 1987 NERC acquired the ISM surface modelling package (Dynamic Graphics Inc, 1986) which uses a minimum surface tension technique for gridding and produces well-behaved grids for line-based and unevenly-spaced data. Using this technique, it was found possible to produce grids of the Lake District data at a 0.25 km interval directly (i.e. without interpolating from a 1 km grid), which were particularly well-behaved and suitable for subsequent image processing. The ISM package was therefore adopted as the standard and used to generate the grids from which all the images shown in this thesis were derived.

An additional factor affecting the quality of images of gravity data, which must be taken into account before gridding, is the density value used for the Bouguer correction when calculating the Bouguer anomaly at each data point. If the wrong density value is used, the resulting Bouguer anomaly values will contain a component which reflects topographic changes (Nettleton 1939). In areas of high topographic relief this effect can be quite significant, especially when enhanced by subsequent image processing techniques, and may obscure gravity variations due to geological structure. Density values vary widely across the Lake District (see Chapter 5) but within the area of greatest topographic relief the Skiddaw, Borrowdale and Windermere groups predominate. A density of 2.75 Mg/m^3 gave the least topography-related 'noise' on test images and was adopted as a reasonable compromise (the gravity images shown below are based on Bouguer anomaly values recalculated using this value).

For the magnetic data, grids of total field values must be reduced to the pole before transfer to the image processing system (this was achieved using a program developed at the USGS and implemented at BGS by Z.K. Dabek and J.P. Williamson). The reduction-to-pole algorithm transforms the field to that which would be measured if the Earth's field was vertical. It gives symmetrical anomalies over vertical bodies with induced magnetization and assists spatial correlation of gravity and (induced) magnetic anomalies due to the same source. However, the algorithm is based on the assumption of induced magnetization in the direction of the present day magnetic field and will not necessarily improve the correlation of anomalies for bodies with a significant remanent component of magnetization such as the Eycott Volcanic Group.

6.3 CREATION OF PRIMARY IMAGES

Image processing systems hold single-field data in byte format within a positive 8-bit range (0-255). The gridded fields must therefore be rescaled into the 0-255 range and converted into a byte-format file compatible with the system. The choice of scaling parameters affects both the visual impact and information content of the final images. The objective is to obtain the maximum resolution of anomalies over the particular range of interest.

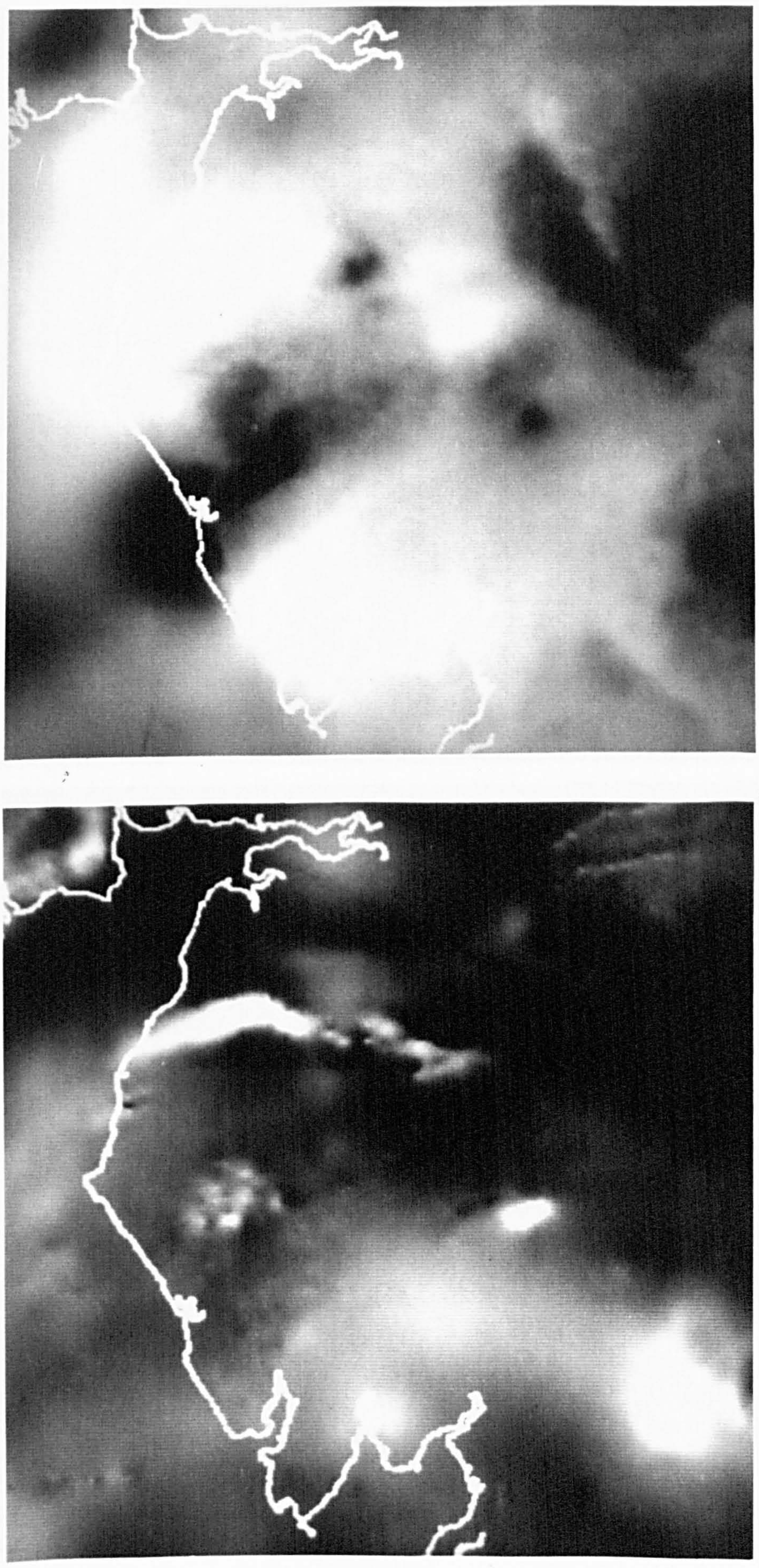
The gridded gravity values for the Lake District area ranged from -28.28 to +26.63 mGal. They were re-scaled using an interval of 0.2 mGal over the range -25.4 mGal (matched to bit 0) to +25.4 mGal (matched to bit 255). Reduced-to-pole magnetic values varied from -190 nT to +440 nT. However most of the highest values occur as sharp anomalies over restricted areas and the main interest lies in the middle of the range. Values were therefore rescaled using an interval of 1.5 nT over the range -190 nT (matched to bit 0) to +191 nT (matched to bit 255). Grid values outside the range were set to 0 or 255 as appropriate. The resulting files were transferred to the I^2S image processing facility where all subsequent processing was carried out. All gridding and pre-processing operations (ie. reduction to the pole and scaling) were carried out on the NERC VAX8600 computer at Keyworth.

The primary fields are displayed initially on the image processor as grey-tone images (black = 0, white = 255). Coloured images may be created by assigning particular values for the red, green and blue guns (in the range 0.0 to 1.0) to particular bands on the grey-scale image. The effectiveness of different colouring schemes depends on the data involved and is largely a matter of subjective judgement. A number of colour tables were tested on the Lake District data and it was found that the simple 26 band blue-red scale shown in Table 6.1 proved the most acceptable. This was stored as a look-up table and used to colour all the images shown in this thesis.

Table 6.1 Look-up table for colouring images

GREY-SCALE RANGE	RED	GREEN	BLUE
	(gun intensities)		
1 - 10	0.0	0.0	0.5
11 - 20	0.0	0.0	0.6
21 - 30	0.0	0.0	0.7
31 - 40	0.0	0.0	0.8
41 - 50	0.0	0.0	0.9
51 - 60	0.0	0.0	1.0
61 - 70	0.1	0.1	1.0
71 - 80	0.2	0.2	1.0
81 - 90	0.3	0.3	1.0
90 - 100	0.4	0.4	1.0
101 - 110	0.5	0.5	1.0
111 - 120	0.6	0.6	1.0
121 - 130	0.7	0.7	1.0
131 - 140	1.0	0.7	0.7
141 - 150	1.0	0.6	0.6
151 - 160	1.0	0.5	0.5
161 - 170	1.0	0.4	0.4
171 - 180	1.0	0.3	0.3
181 - 190	1.0	0.2	0.2
191 - 200	1.0	0.1	0.1
201 - 210	1.0	0.0	0.0
211 - 220	0.9	0.0	0.0
221 - 230	0.8	0.0	0.0
231 - 240	0.7	0.0	0.0
241 - 250	0.6	0.0	0.0
251 - 255	0.5	0.0	0.0

Grey-scale and colour images of the gravity and reduced-to-pole aeromagnetic data for the Lake District are shown in Figures 6.1 and 6.2 respectively. The coastal outline was created from a digitized coastline file by generating a byte-format file in which pixels containing digitized points were assigned the value 255 and all other pixels were assigned the value zero. This was then superimposed onto the grey and colour images using the in-built image processor funtions. Although the colour images provide information on anomaly amplitude, they convey less information on gradients than traditional contour maps. On their own, the grey-scale and colour images are not



A

B

Figure 6.1 Grey-scale images of Lake District (a) Bouguer anomaly and (b) aeromagnetic anomaly (reduced to pole).

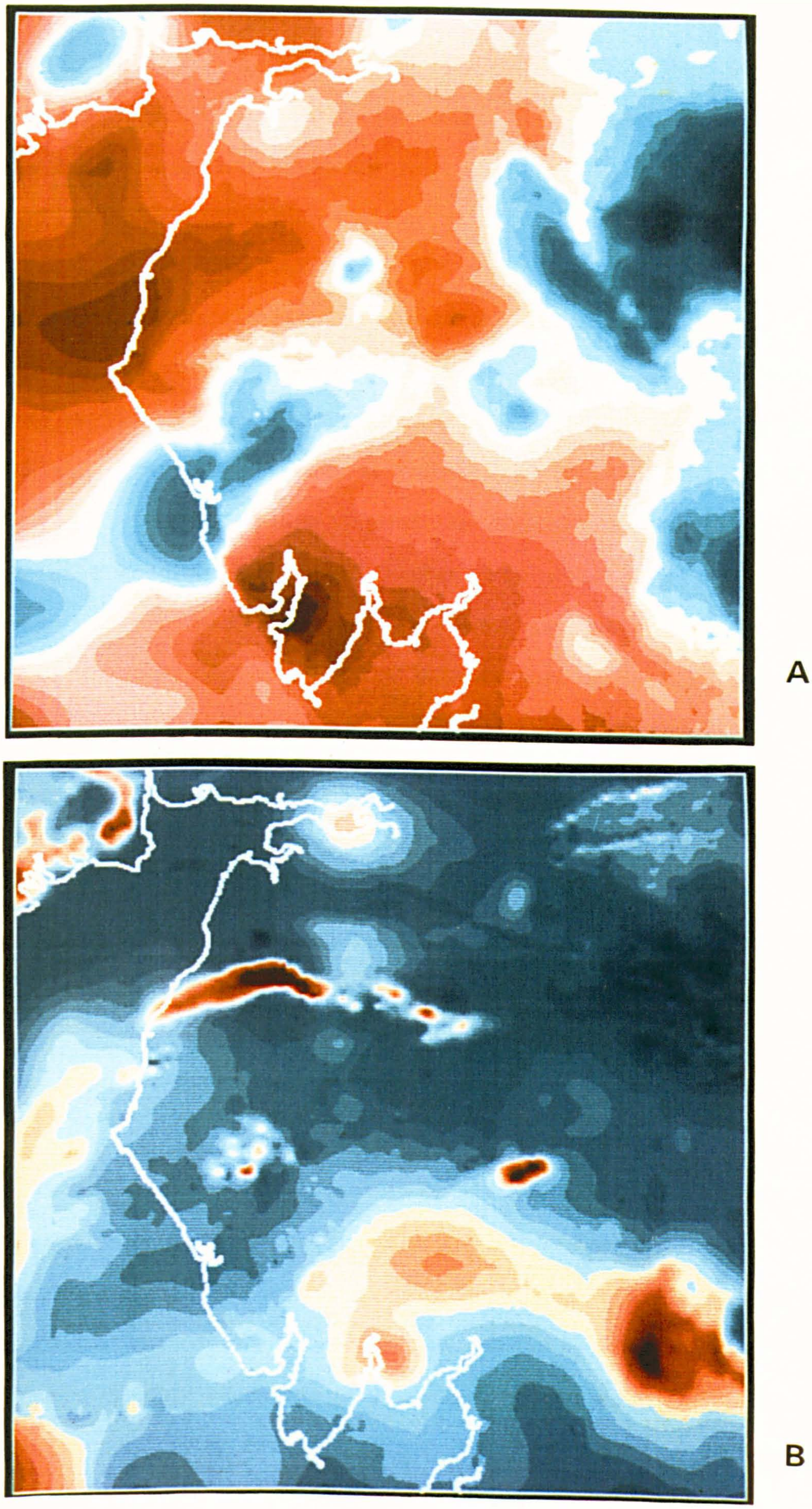


Figure 6.2 Flat-colour images of Lake District (a) Bouguer anomaly and (b) aeromagnetic anomaly (reduced to pole).

particularly informative but they represent the primary information from which other images are created.

6.4 SHADED RELIEF PRESENTATIONS

Shaded-relief presentations are based on the concept of creating the visual illusion of topography by treating the primary field as a topographic surface illuminated from a certain direction. A number of techniques exist for creating shaded images from gridded data but the method usually used on image processing systems is to apply a two-dimensional gradient transform to the grey-scale image. This is similar to a first derivative operation in the direction of the gradient and although not strictly the mathematical equivalent of true artificial illumination, the result is visually very similar.

For example, the illusion of illumination from the north may be achieved by the application of a convolution kernel of the form:

$$\begin{matrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{matrix}$$

The value assigned to each pixel after convolution is a function of the filter pass direction and the magnitude and direction of the local slope (Drury & Walker 1987). In the above example, anomaly gradients facing towards the north become positive after convolution while gradients facing south become negative. After rescaling, slopes towards the filter appear brightly lit while those facing away appear as if in shadow (Drury & Walker 1987).

The choice of kernel size and direction of bias are dependent on the nature of the data and the objective of the analysis. Two images illuminated from separate directions at right angles are usually sufficient to detect the most important structural trends inherent in any particular gravity or magnetic field. The I^2S system has an built-in function (COMPASS) which applies a simple 3x3 kernel of the type illustrated above in any user-defined direction. Alternatively, the user may design his own kernel with different characteristics which is then used as an operator on the grey-scale image using another of the I^2S built-in functions (CONVOLVE).

In the case of the Lake District data, a number kernels of size 3x3, 5x5 and 7x7 were tested for their effectiveness for delineating subtle anomalies and structural trends. The most effective for use on the images derived from 0.25km grids (see above) were found to be 5x5 kernels of the form:

1.00	0.75	0.50	0.25	0.00
0.75	0.50	0.25	0.00	-0.25
0.50	0.25	0.00	-0.25	-0.50
0.25	0.00	-0.25	-0.50	-0.75
0.00	-0.25	-0.50	-0.75	-1.00

The above example simulates illumination from the northwest. A plot of the directional and frequency response of the kernel is shown in Figure 6.3 (calculated using unpublished software by C.A. Green, BGS). The plot demonstrates that it acts as a directional band-pass filter with a peak response at a normalized frequency of 0.08 (equivalent to anomalies of wavelength around 3 km for a 0.25 km grid)

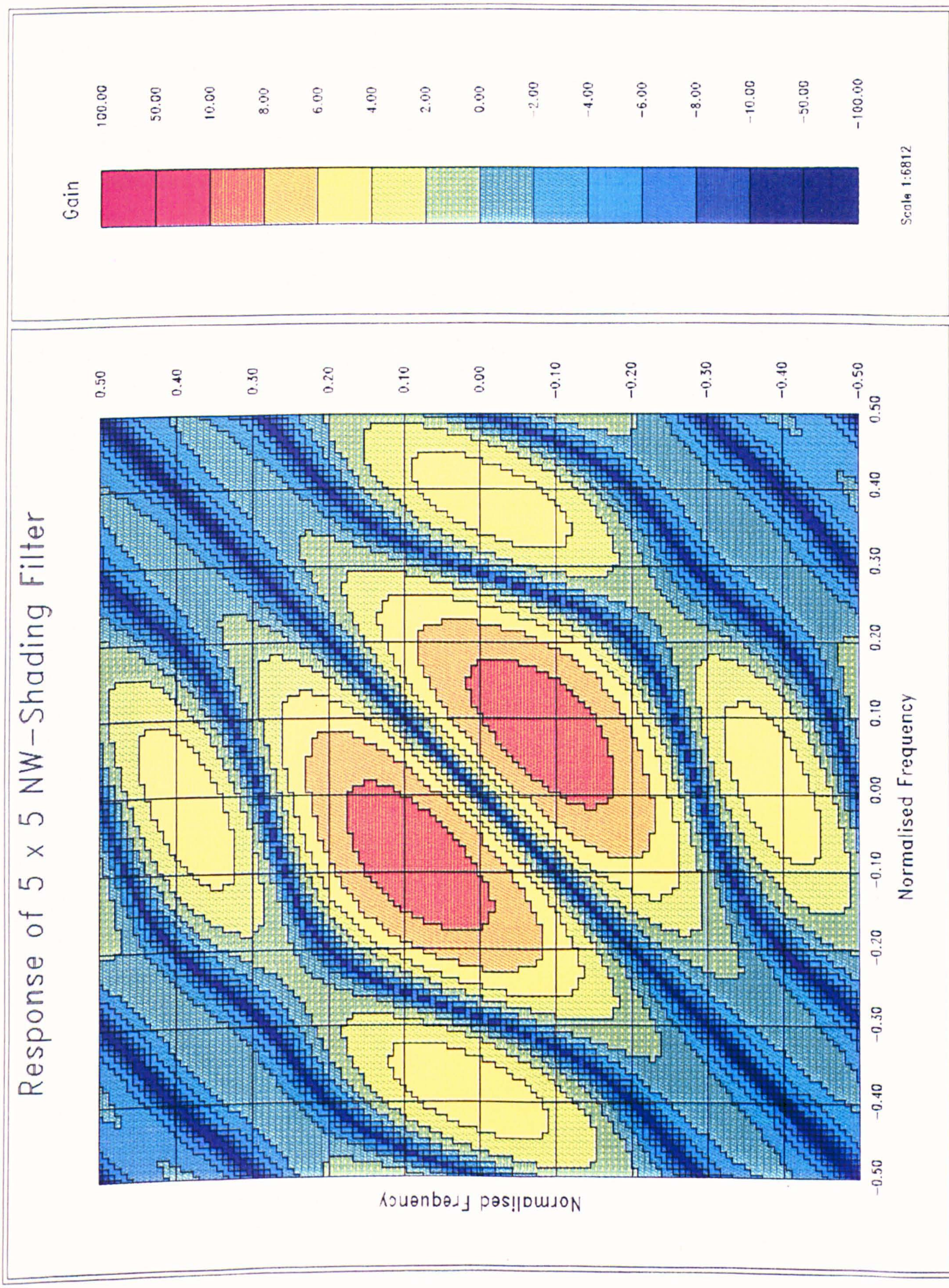
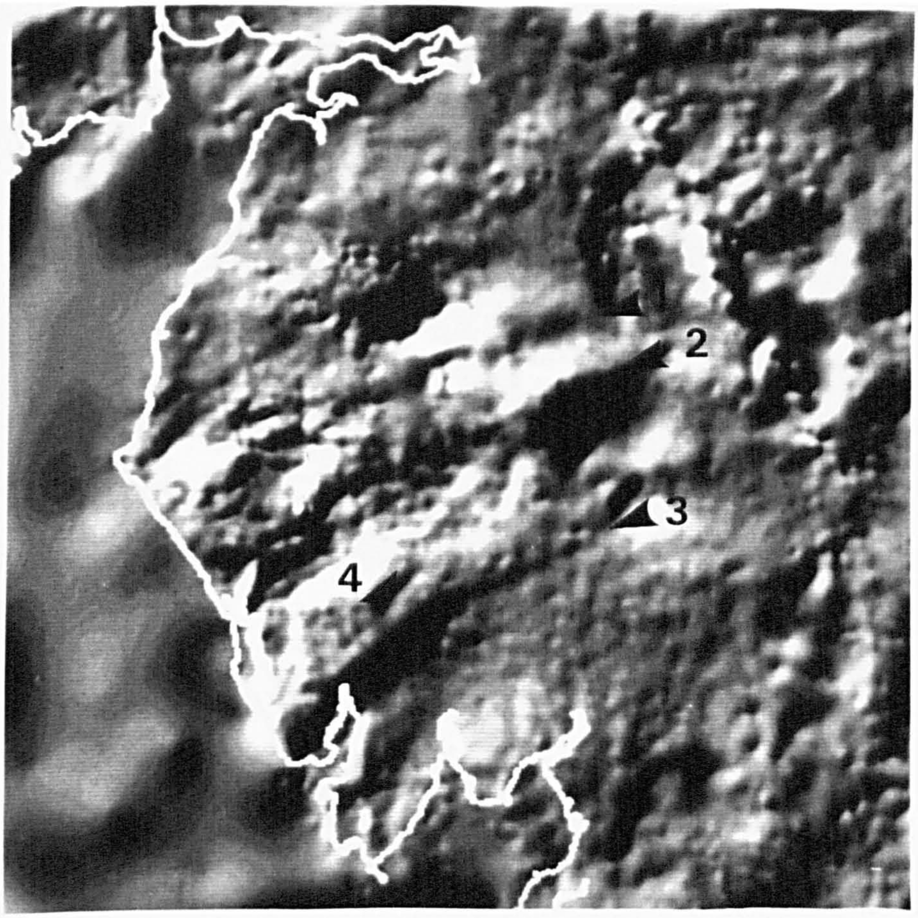


Figure 6.3 Directional and frequency response of a 5 x 5 northwest directional gradient filter.

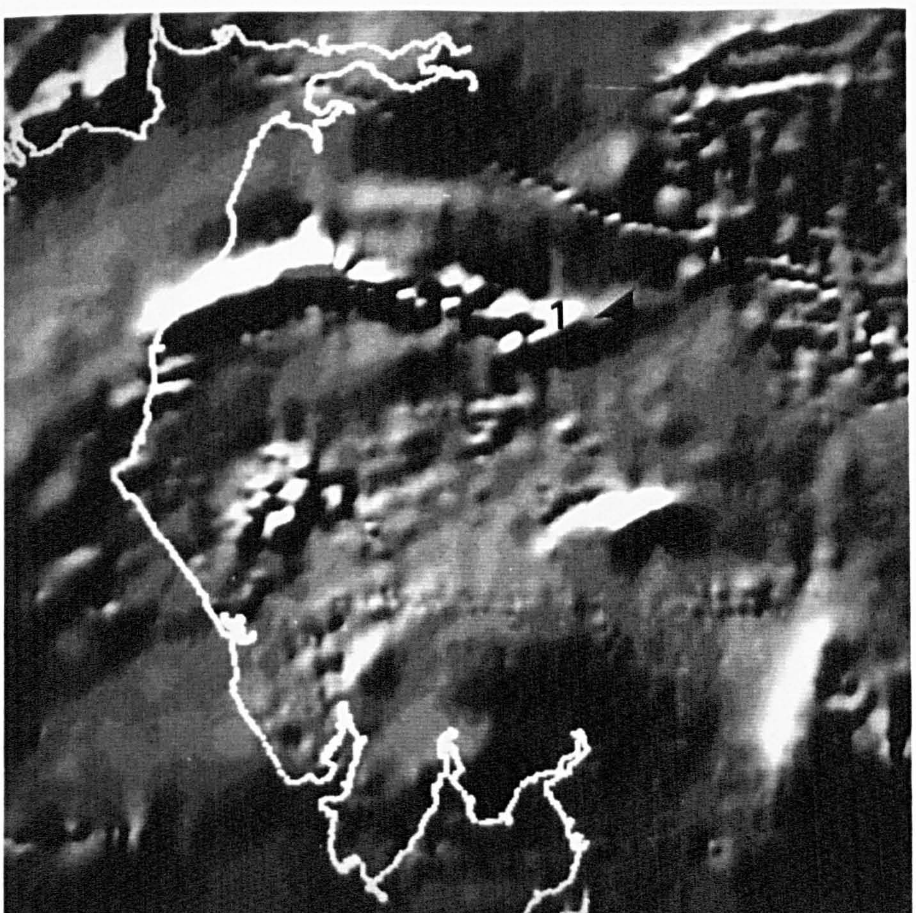
trending in a north-easterly direction. Thus, when convolved with the grey-scale images, the resulting shaded-relief images (Figure 6.4) enhance density and magnetization contrasts in the upper few kilometres of the crust with a Caledonian (NE) trend. Note, however, that the response of the kernel is not simple; there are significant side lobes at a wavelength of around 0.6 km in the N-S and E-W directions. The orthogonal kernel simulating illumination from the northeast has the effect of enhancing structures with a Permo-Triassic (NNW) trend (Figure 6.5). Used in conjunction, therefore, these kernels enhance the two most important directions of structural control on the evolution of both the Lower Palaeozoic inlier and the post-Caledonian sedimentation.

The production of colour shaded-relief images involves the simple multiplication of the grey-scale shaded images and their flat-colour counterparts. Colour-shaded images of the Lake District gravity and aeromagnetic data illuminated from the northwest are shown in Figure 6.6. They combine information relating to anomaly gradient (relief) with that relating to anomaly amplitude (colour) and when compared with the original contour maps (Figures 2.3 and 2.7) the increased information content, particularly that relating to gradients and lineaments, is clearly apparent. The principal features are briefly described below but their significance is discussed in detail in Section 6.7. The reader is referred to Figures 2.3 and 2.7 for identification of the major anomalies.

On the NW illuminated gravity images (Figures 6.4a and 6.6a) the most interesting features are the ENE trending lineaments across the Lake District Lower Palaeozoic inlier (1, 2 and 3, Figure 6.6a) and the suggestion of a more northeasterly trending lineament across the

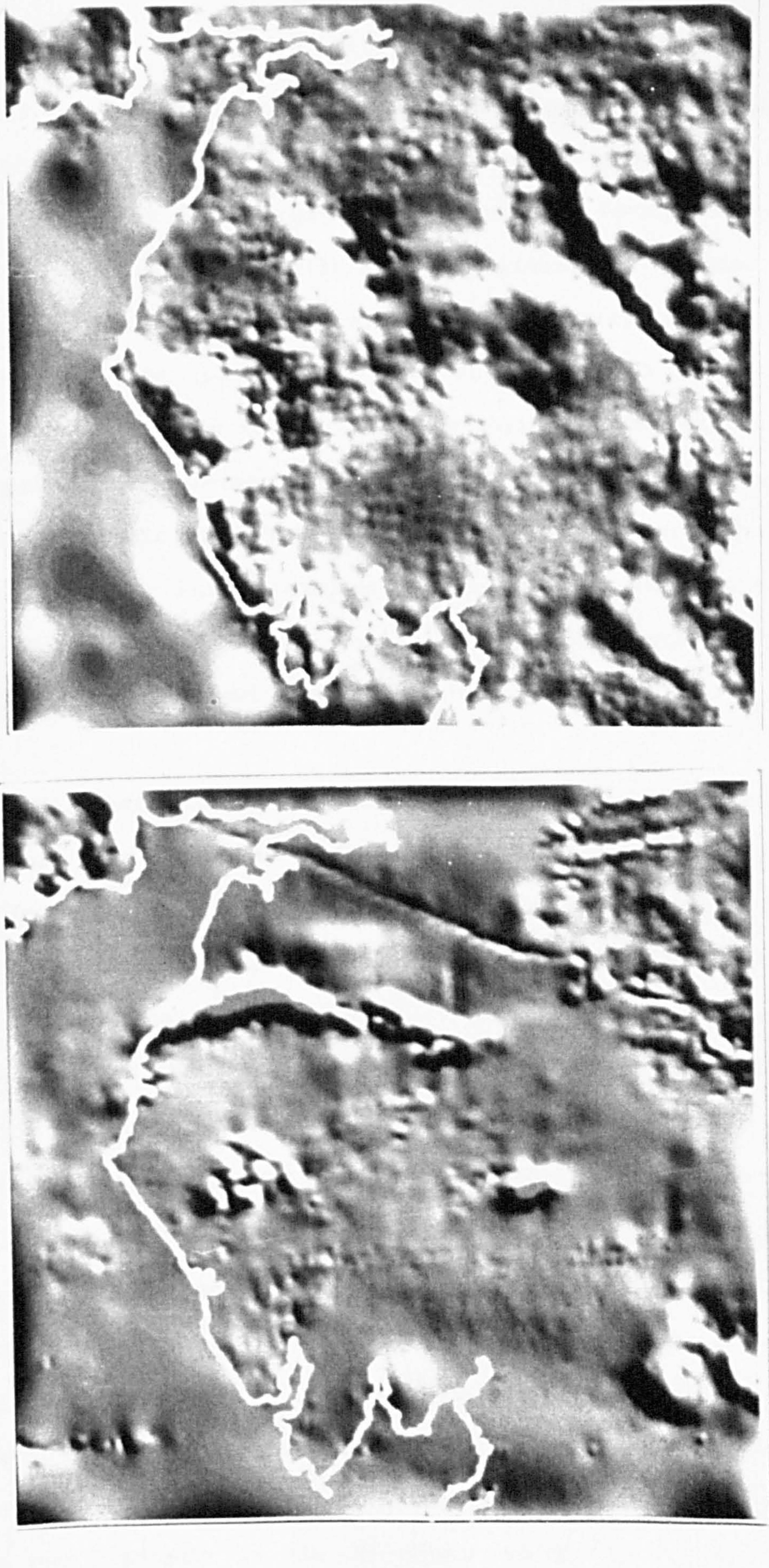


A



B

Figure 6.4 Northwest-illuminated, grey-shaded images of Lake District (a) Bouguer anomaly and (b) aeromagnetic anomaly (reduced to pole). Numbers indicate lineaments discussed in the text.



A

B

Figure 6.5 Northeast-illuminated, grey-shaded images of Lake District (a) Bouguer anomaly and (b) aeromagnetic anomaly (reduced to pole).

outcrop of the Borrowdale Volcanic Group (4 Figure 6.6a). Lineament 1 crosses the southern part of the main Skiddaw Group inlier close to the line of the Causey Pike Thrust and the recently identified contact between the northern and southern tracts within the Skiddaw Group (Figure 1.3). Lineament 2 lies close to the outcrop of the Airy's Bridge Formation on the northern limb of the Scafell Syncline and continues eastwards into to the Ullswater inlier of the Skiddaw Group (see Figure 1.3). Lineament 3 lies along the contact between the Borrowdale Volcanic and Windermere groups in the southern Lake District. The major linear features outside the Lake District are the Dent and Pennine fault systems, the latter showing up particularly well on the NE illuminated gravity image (Figure 6.5a).

The NW illuminated magnetic images (Figures 6.4b and 6.6b) show a similar, but more subtle set of ENE-trending lineaments as the gravity images. In particular, the magnetic images show that lineament 1 also marks the southern limit of the highly magnetic lavas of the Eycott Volcanic Group. The effectiveness of shaded images for delineating minor features in the presence of larger anomalies is illustrated by the narrow WNW trending magnetic low across the northern part of the images which traces the line of the (Tertiary) Cleveland-Armathwaite Dyke. Although visible on the contour map (Figure 2.7) the feature is much clearer and easier to follow on the images. The 'pitting' along the anomaly is a gridding artifact related to the fact that the original survey was carried out along flight lines 2 km apart. Other features of note on the magnetic images are the linear anomalies in the NE corner which correspond to outcrops of the (Carboniferous) Whin Sill and the ovoid anomaly in the NW corner which corresponds to the marginal varieties of the Criffel Granodiorite around the (presumably)

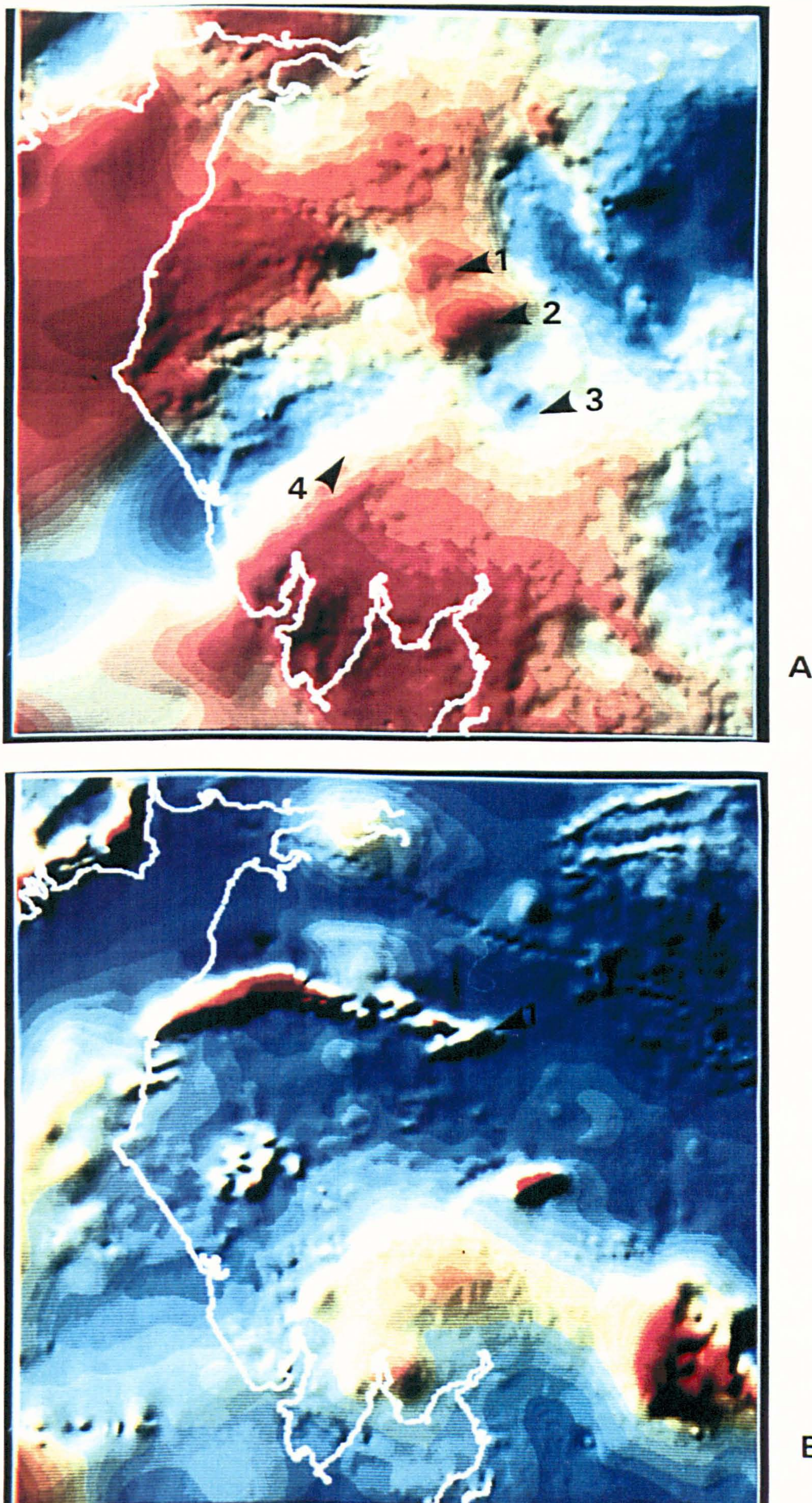


Figure 6.6 Northwest-illuminated, colour-shaded images of Lake District (a) Bouguer anomaly and (b) aeromagnetic anomaly (reduced to pole). Numbers indicate lineaments discussed in the text.

less magnetic, acid central part of the intrusion (Bott & Masson Smith 1960).

6.5 RESIDUAL AND DERIVATIVE FIELDS

The separation of 'regional' and 'residual' fields and the calculation of derivatives are both traditional methods used for analysing potential field data. These have been combined with image processing techniques in order to analyse minor anomalies and subtle trends in the Lake District in more detail.

6.5.1 Residual fields

A method commonly used for separating anomalies due to relatively near-surface bodies from regional gradients and those due to deeper structures, is to calculate and subtract from the original data a low-order polynomial trend surface. The process is, essentially, one of separating the longer and shorter wavelength anomalies and is not to be confused with defining a 'background' field against which to carry out quantitative modelling (see Section 7).

The choice of a surface to represent the 'regional' field depends on the objective of the analysis and the wavelength of the anomalies to be isolated in the 'residual' field. In the case of the gravity data the objective was to remove regional gradients and the effects of the deeper parts of the batholith in order to isolate anomalies due to (a) individual components of the batholith, and (b) small amplitude anomalies due to minor intrusions and structures within the upper few kilometres of the Skiddaw and Borrowdale Volcanic groups. Likewise for the magnetic data, the objective was to remove the influence of longer wavelength anomalies, in particular the large deep-seated high in the southern Lake District, in order to study minor anomalies and trends over the Lower Palaeozoic outcrop.

A series of non-orthogonal polynomial surfaces, of various orders, were calculated from the primary gravity and (reduced to pole) magnetic field grids (BGS software, C.A. Green) and subtracted from the original grids. Thes were then converted to byte format, as described in Section 6.3, and transferred to the image processor for evaluation and subsequent analysis. In the case of both the gravity and magnetic fields it was found that 'regional' fields represented by surfaces of order 10 met most of the objectives outlined above. Flat-colour images of the 10th order regional gravity and (reduced to pole) magnetic fields, and the corresponding residual fields, are shown in Figures 6.7 and 6.8. These were generated by applying the standard colour table to byte-format grey-scale images as described in Section 6.3.

As with the primary fields, a 5 x 5 gradient transform kernel was applied to the residual fields to generate grey-shaded images. These were multiplied by the flat-colour images to achieve colour-shaded representations of the residual fields. Images of the residual gravity and magnetic fields illuminated from the NW are shown in Figure 6.9. On the gravity image (Figure 6.9a) the negative anomalies over the exposed granitic intrusions and the lineaments identified previously (Figure 6.6a) are more clearly identified. The removal of the steep gradients associated with the northern and southern margins of the batholith has increased the resolution of features in these areas, for example the contact between the Borrowdale Volcanic Group and the (lower density) Windermere Group in the southern Lake District (related to lineament 3). In addition, minor anomalies and subtle trends over

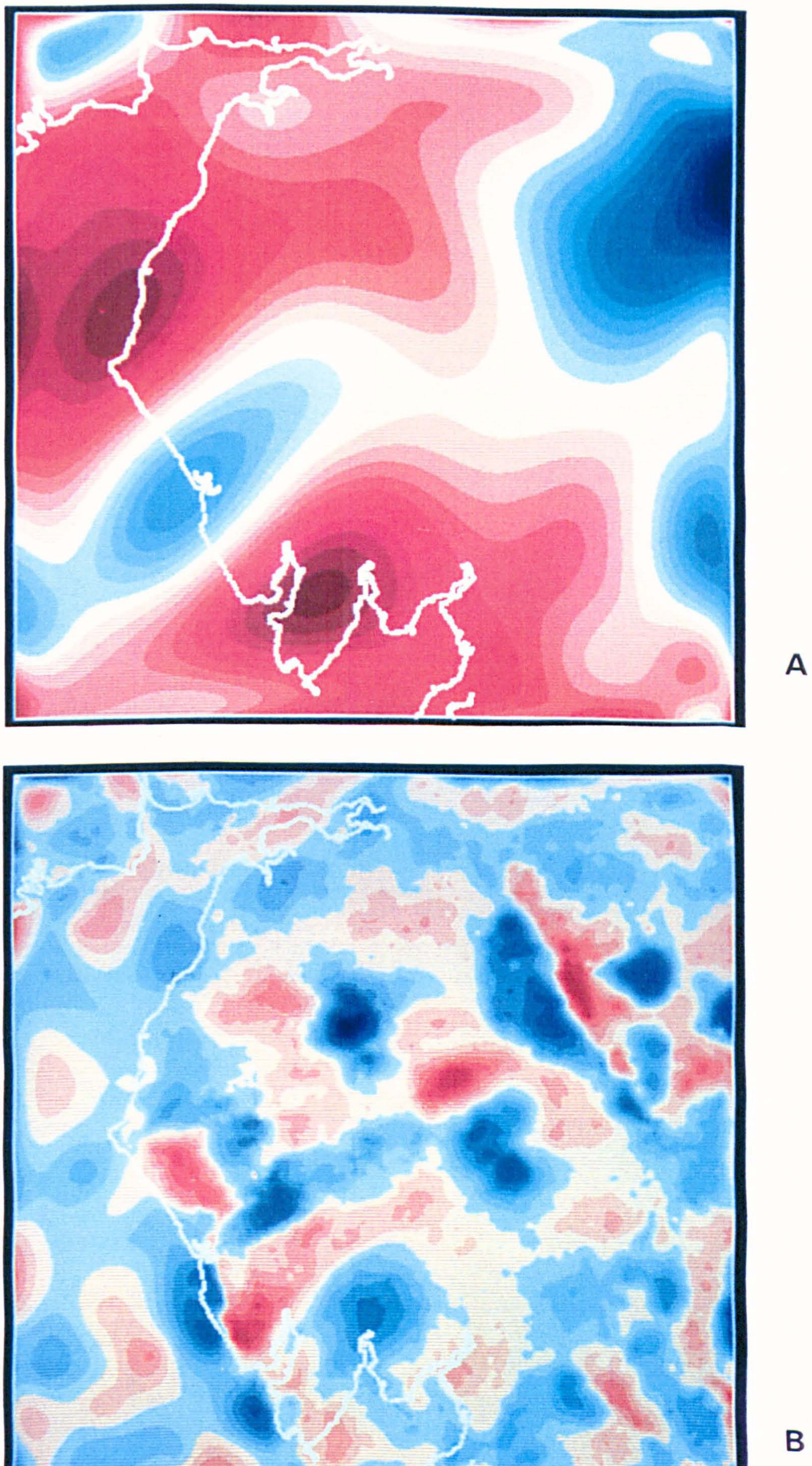


Figure 6.7 Flat-colour images of (a) 'regional' gravity field represented by 10th order non-orthogonal polynomial surface and (b) residual gravity field represented by subtracting the regional from the observed field.

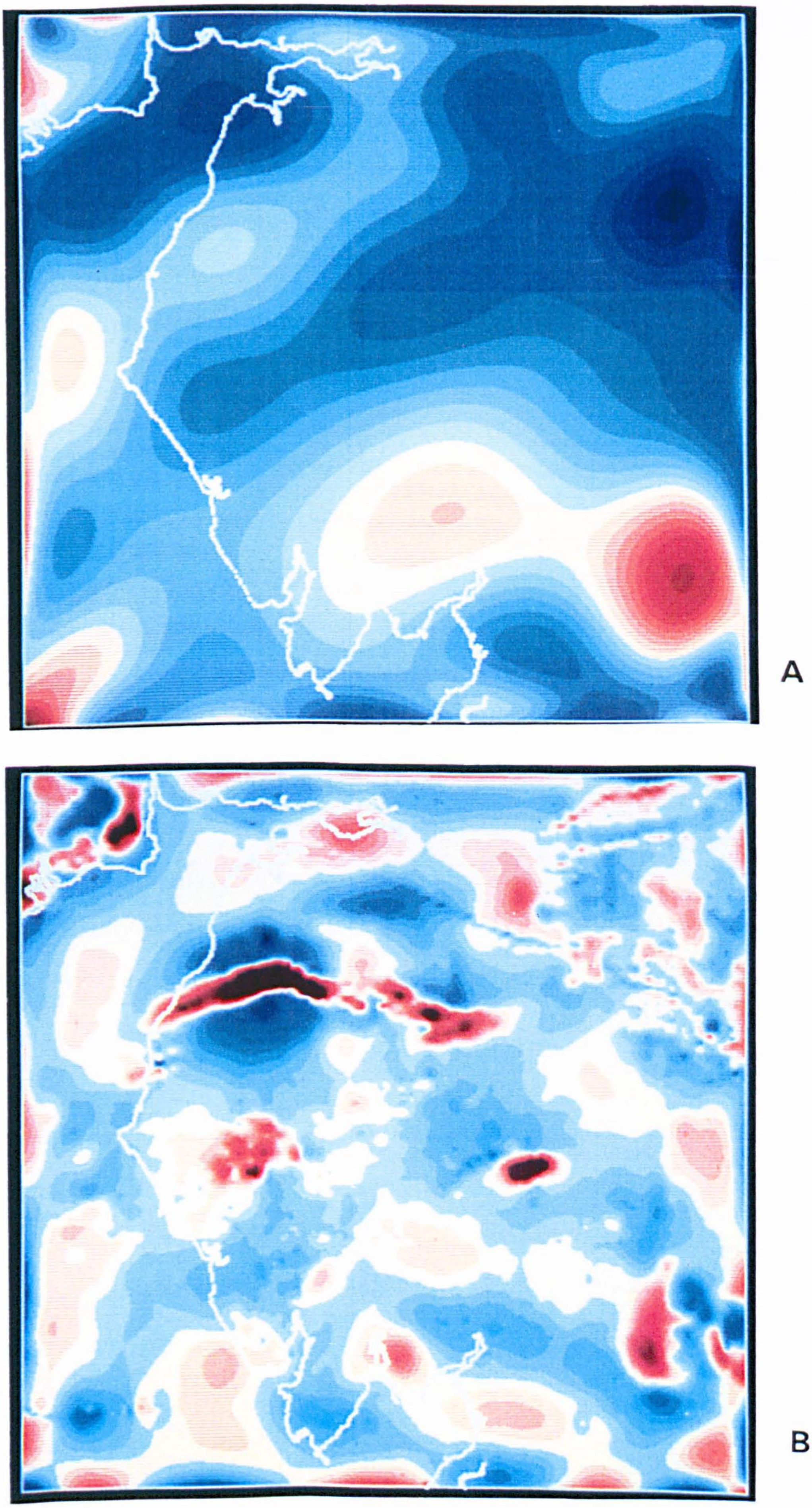


Figure 6.8 Flat-colour images of (a) 'regional' magnetic field represented by 10th order non-orthogonal polynomial surface and (b) residual magnetic field represented by subtracting the regional from the observed field.

exposed Skiddaw Group and Borrowdale Volcanic Group rocks are more clearly resolved in the central Lake District. Likewise the residual magnetic image (Figure 6.9b) more clearly resolves anomalies and lineaments within the Lower Palaeozoic inlier. The significance of the features is discussed in more detail in Section 6.7.

6.5.2 Derivative fields

A number of techniques exist for generating first and second derivatives of potential field data, both by operating directly on the gridded data and by using user-defined or built-in filter kernels on the I^2S image processing system. The usual objective of displaying derivative fields is to identify the gravity and magnetic gradients associated with the most important density and magnetization contrasts in the upper few kilometres of crust, in which case the result can be likened to a high-pass filter which suppresses long wavelength (i.e. deep seated) features. However, in theory the calculation can be tuned to emphasize gradients corresponding to any defined wavelength of anomaly. Two techniques were evaluated for their effectiveness on the Lake District data.

The first of these uses I^2S function ROBERTS to compute the horizontal gradient vector of an image. This function operates by performing two two-dimensional spatial convolutions in the x and y directions. The resultant image has pixel values defined by:

$$P(x,y) = (X^2 + Y^2)^{0.5}$$

where X and Y are convolutions using the following 2 x 2 kernels:

$$\begin{matrix} 0 & -1 \\ 1 & 0 \end{matrix} \quad \& \quad \begin{matrix} -1 & 0 \\ 0 & 1 \end{matrix}$$

This function was designed primarily as an edge detector. When operated on the primary grey-tone gravity and (reduced to pole) magnetic images (Figures 6.1 a & b) the results (not shown) had a rather stepped or contour-like appearance and were not particularly useful for geological analysis. However, shaded-relief versions, generated by the application of a 5 x 5 gradient transform of the type described in Section 6.4 proved to be a particularly effective means of delineating gradients related to density and magnetization contrasts originating in the very near surface (i.e. the highest frequency geologically-related information contained in the images). Shaded-gradient images of the gravity and magnetic fields illuminated from the north and west are shown in Figures 6.10 and 6.11 respectively. In order to relate the gradient information more closely to the original anomalies the flat-colour images of the primary fields (Figure 6.2 a & b) were multiplied with the north-illuminated shaded-gradient images. The results are shown in Figure 6.12 a & b.

Steep gradients (either positive or negative) over near-surface density and magnetization contrasts are represented by highs on these gradient images; thus granite outcrops are characterized by a ring of highs around a central low. The near-surface expressions of the linear features identified on previous images are well defined as sharp lineaments. The gravity images are particularly effective for defining minor changes of gradient associated with small density contrasts. In addition, the west-illuminated gravity image (Figure 6.10b) displays a subtle grain in which the predominant components trend NW-SE and NE-SW.

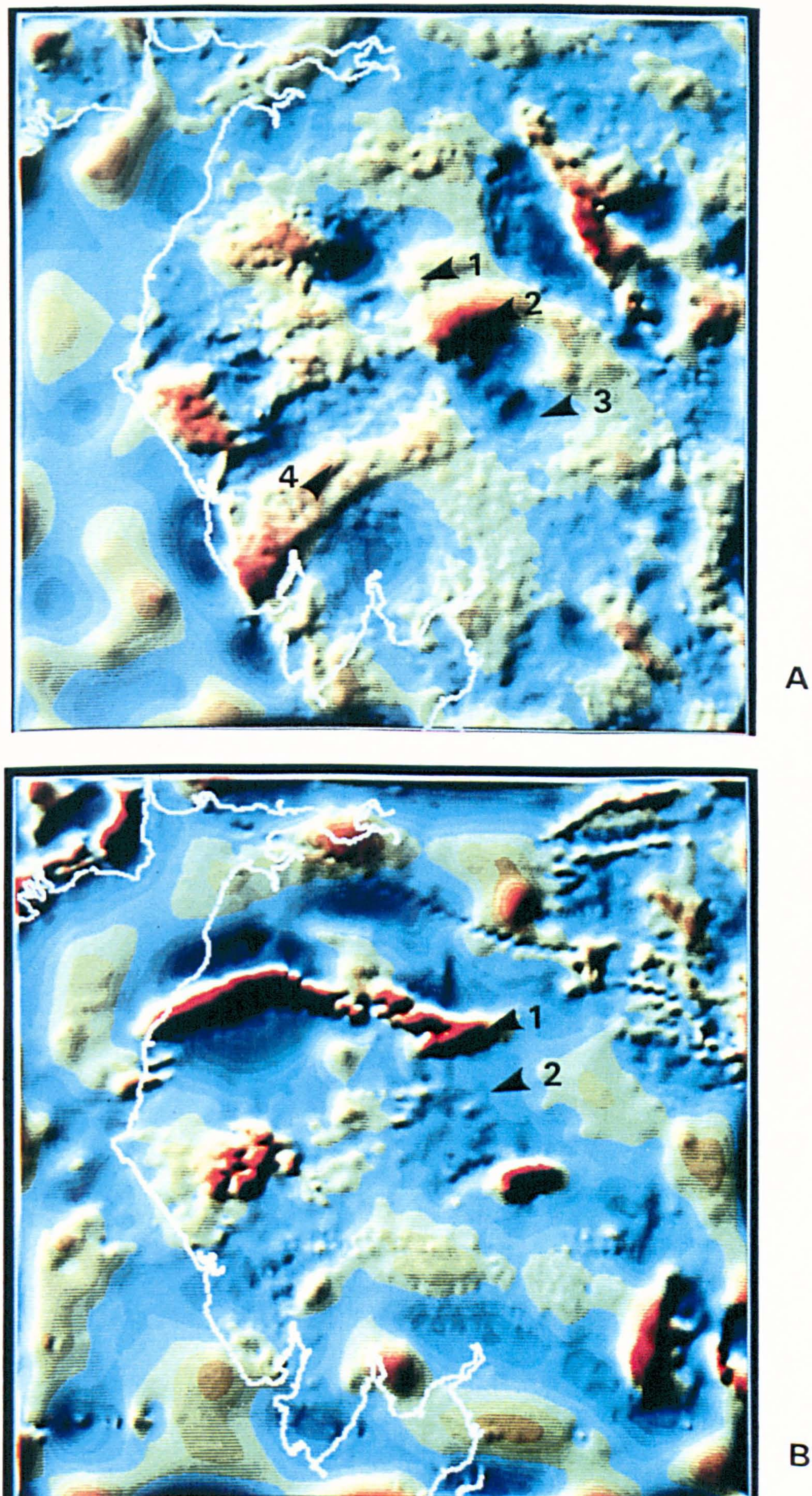
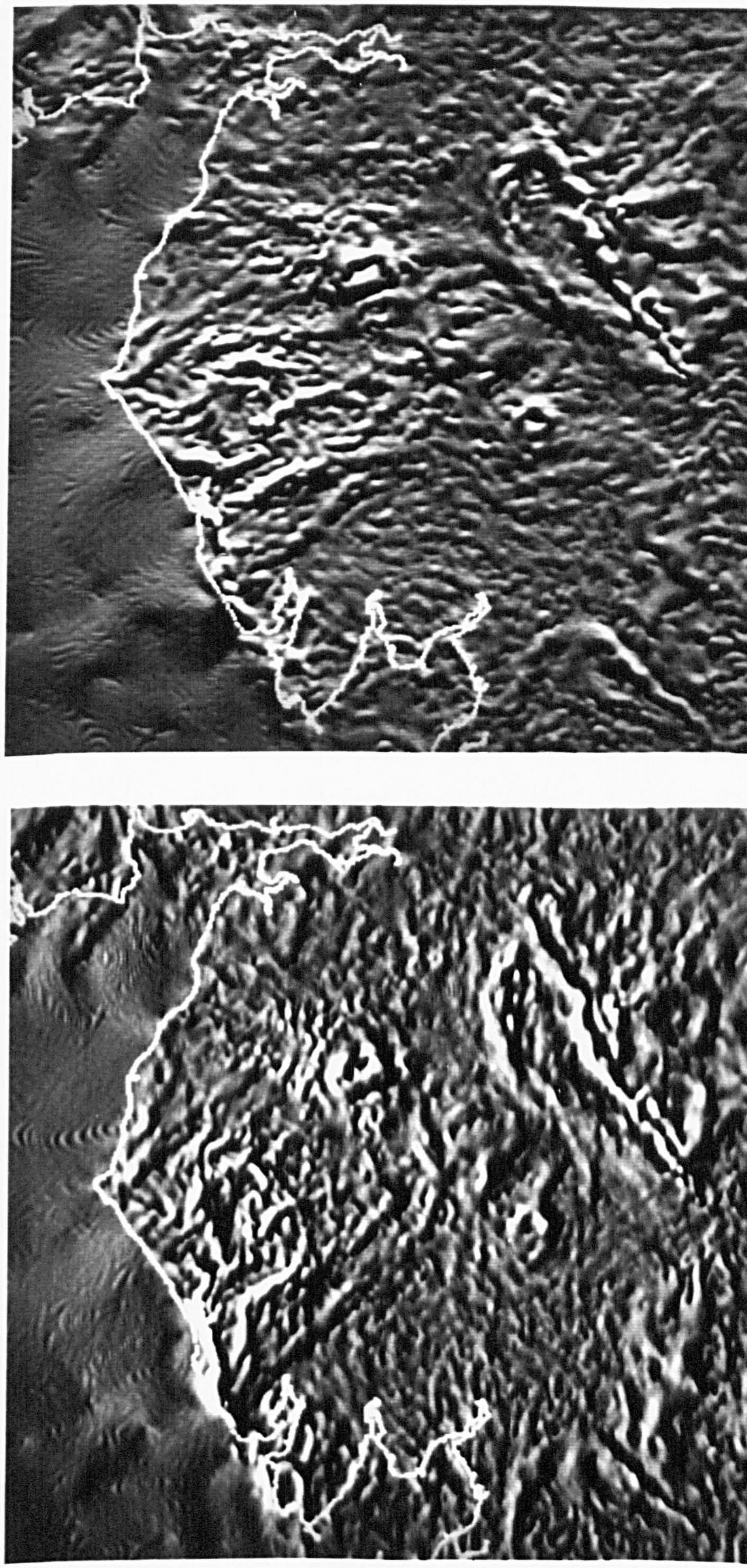


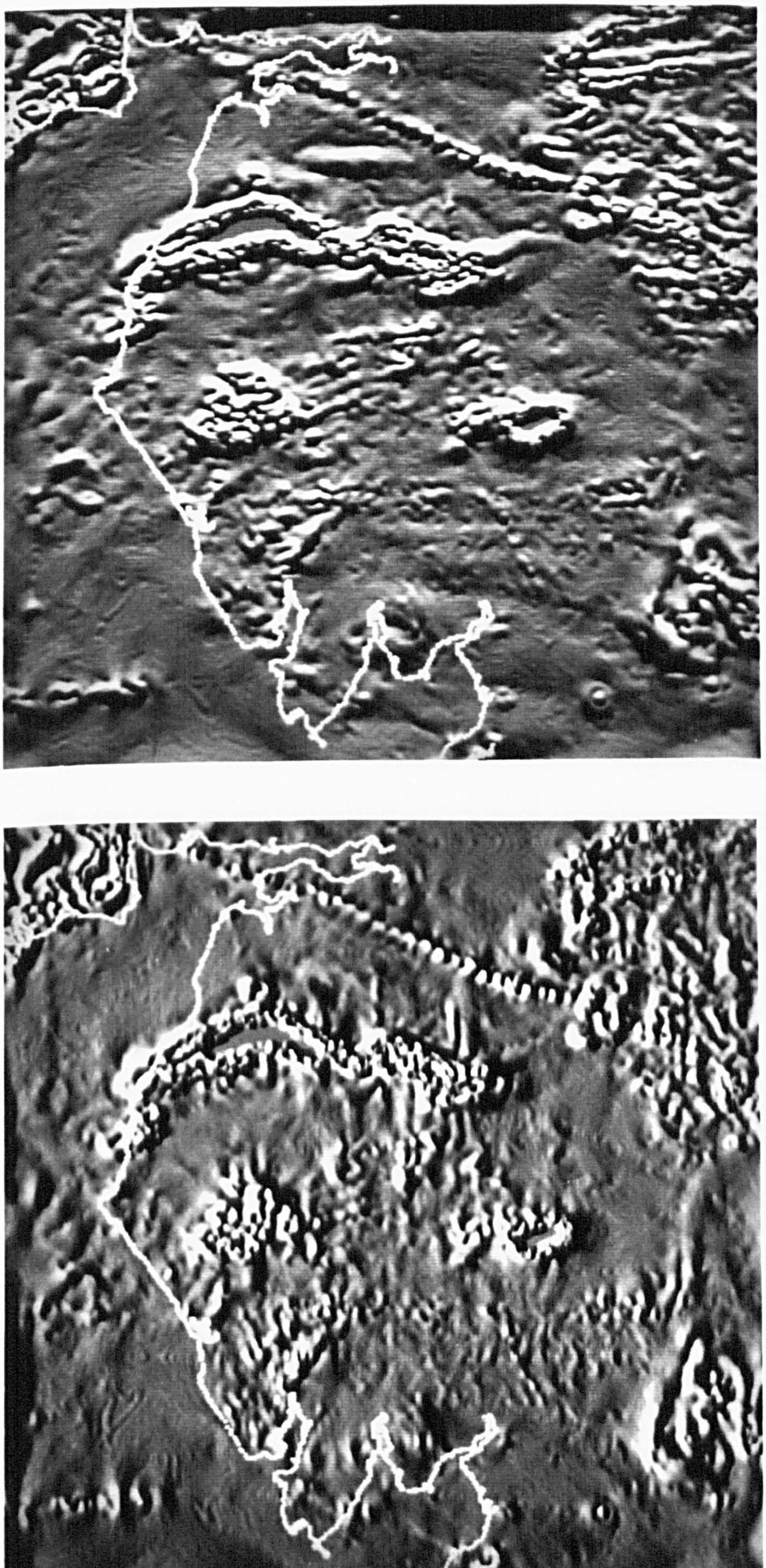
Figure 6.9 Northwest-illuminated, colour-shaded images of (a) residual gravity field and (b) residual magnetic field. Numbers indicate lineaments discussed in the text.



A

B

Figure 6.10 Shaded horizontal gradient of gravity field (a) north-illuminated, (b) west-illuminated.



A

B

Figure 6.11 Shaded horizontal gradient of magnetic field (a) north-illuminated, (b) west-illuminated.

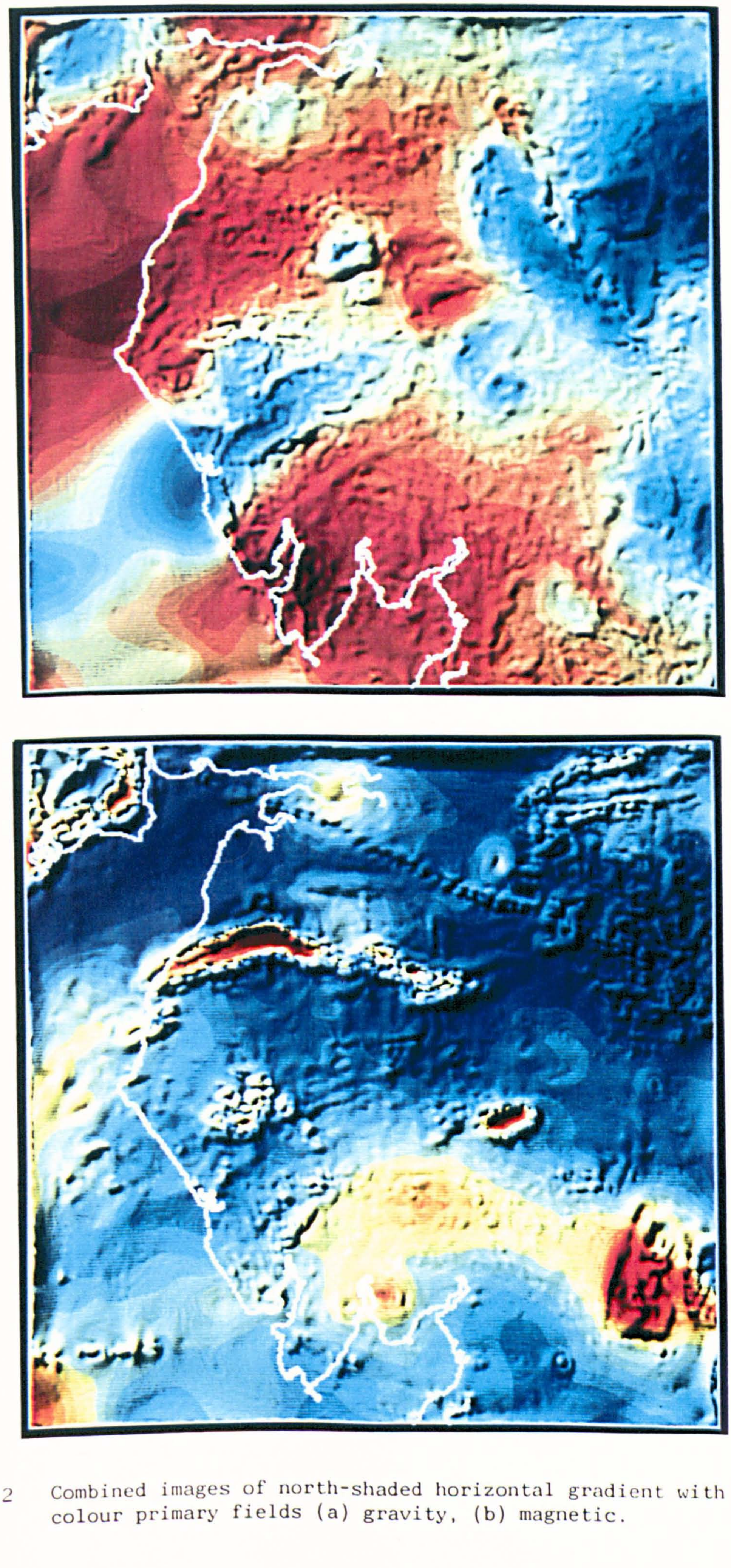


Figure 6.12 Combined images of north-shaded horizontal gradient with flat colour primary fields (a) gravity, (b) magnetic.

However, such features should be treated with caution and only those which can be identified on several images should be considered as significant. It should also be noted that, while the images contain much geologically-related information, the technique has the effect of enhancing some non-geological 'noise' related to data quality and the gridding procedure - for example the corrugation along linear magnetic anomalies such as the Armathwaite dyke which is due to the use of a 0.25 km gridding interval for data collected along flight lines 2 km apart.

The second technique was applied to the gravity data only and involved the calculation of the second vertical derivative according to the method of Elkins (1951). Contour maps of the gravity second vertical derivative have traditionally been used to identify important density boundaries. Positive second derivative anomalies occur on the high density side of a boundary and negative anomalies occur on the low density side; the relative magnitudes of the positives and negatives can sometimes be diagnostic of the direction of slope of the density contact (Bott 1962, Bott et al. 1978). In the present case images of the second vertical derivative were generated on the I^2S by convolving a spatial filter kernel with the primary gravity image. The design of the filter can be tuned to emphasize gradients due to anomalies of a particular wavelength (i.e. density contrasts at a particular depth) and in this respect can be likened to a band-pass filter.

The proceedure finally adopted, which gave the geologically most useful result, was as follows:

(1) Subsampling the primary image (created from a 0.25 km grid) to generate a grey-tone image based on one pixel per kilometre.

(2) Convolving this with the following 9 x 9 kernel designed to calculate the second derivative at twice the pixel interval (i.e. 2 km, Elkins 1951):

0	0	-0.02419	0	0	0	-0.02419	0	0
0	0	0	0	0	0	0	0	0
-0.02419	0	-0.012097	0	0.01613	0	-0.012097	0	-0.02419
0	0	0	0	0	0	0	0	0
0	0	0.01613	0	0.1774	0	0.01613	0	0
0	0	0	0	0	0	0	0	0
-0.02419	0	-0.012097	0	0.01613	0	-0.012097	0	-0.02419
0	0	0	0	0	0	0	0	0
0	0	-0.02419	0	0	0	-0.02419	0	0

(3) Re-scaling the output into the 0 - 255 range and expanding the result back to a scale of 1 pixel per 0.25 km (to register with the other images) by bi-linear interpolation.

A flat-colour image of the gravity second vertical derivative generated in this way is shown in Figure 6.13a. However, as with the other images the application of a 5 x 5 gradient transform to achieve a shading effect proved particularly effective, especially when combined with the flat-colour image to give a colour shaded presentation (Figure 6.13b). This image emphasizes anomalies which originate at a depth of a few kilometres. Long wavelength features such as the effects of the deeper parts of the batholith are suppressed, as are those due to very near surface contrasts which dominated the horizontal gradient images discussed above (e.g. Figure 6.10). The most prominent features, therefore, relate to the upper parts of the individual intrusions which make up the granite batholith and to significant density contrasts within the Lower Palaeozoic basement and Upper Palaeozoic cover rocks. The lineament identified on Figure 6.6 as 1 is especially prominent on Figure 6.13b, suggesting that it may be a line of significant importance during the evolution of the area. The exposed granites are characterized by second derivative lows surrounded by highs (Bott 1962) and the pattern of anomalies over the Skiddaw and Borrowdale Volcanic Groups is probably related to both concealed granite cupolas and structures within those groups. The significance of the anomalies is discussed in more detail in Section 6.7.

6.6 DATA INTEGRATION AND CORRELATION OF ANOMALIES

In addition to their image enhancement capabilities, image processing systems provide a powerful medium for integrating and jointly analysing a number of different datasets. In the case of the Lake District, the principal objectives were to examine the relationship between the gravity and magnetic anomalies and to identify common trends and lineaments.

One of the simplest, but most effective methods of examining the relationship between two datasets (i.e. gravity and magnetic fields) is to display one as contour lines overlaying a flat-colour or colour-shaded image of the other. Figure 6.14 shows a pair of images comprising (a) contours of the reduced-to-pole magnetic field overlaying a colour shaded gravity image and (b) gravity contours overlying the colour-shaded magnetic field. These images demonstrate the spatial relationship of anomalies such as that between the gravity low and short wavelength magnetic highs over the Ennerdale Granophyre (EN, Figure 6.14a). Similarly, they demonstrate the way in which the prominent magnetic anomaly over the Eycott Volcanic Group is interrupted across the Skiddaw Granite (which is characterized by a gravity low, feature SK) presumably because the early Devonian (non-magnetic) granite has cut out and/or altered the earlier Eycott Volcanic rocks. Features of interest outside the Lake District include: (1) the correlation of the major magnetic high in the Solway Basin (feature CLB) with a minor gravity high between two gravity lows, and (2) the relationship between the gravity low over the central part of the Criffel Granodiorite (feature CR) and the annular magnetic high over the margins of the intrusion.

More sophisticated combinations may be used to examine the relationship between gravity and magnetic lineaments and short wavelength features. Figure 6.15 shows a composite image comprising the northwest-illuminated, colour-shaded gravity second vertical derivative image (Figure 6.13b) multiplied with the northwest-illuminated, grey-shaded magnetic horizontal gradient image (similar to those shown in Figure 6.11a). This combination highlights the relationship between the most important, near-surface magnetic anomalies and the gravity features (both lineaments and anomalies) originating within the upper parts of the batholith and Lower Palaeozoic sequence. For example, it shows that gravity lineament 1 (see Figure 6.13b) appears to coincide roughly with the southern limit of the magnetic anomaly due to the Eycott Volcanic Group.

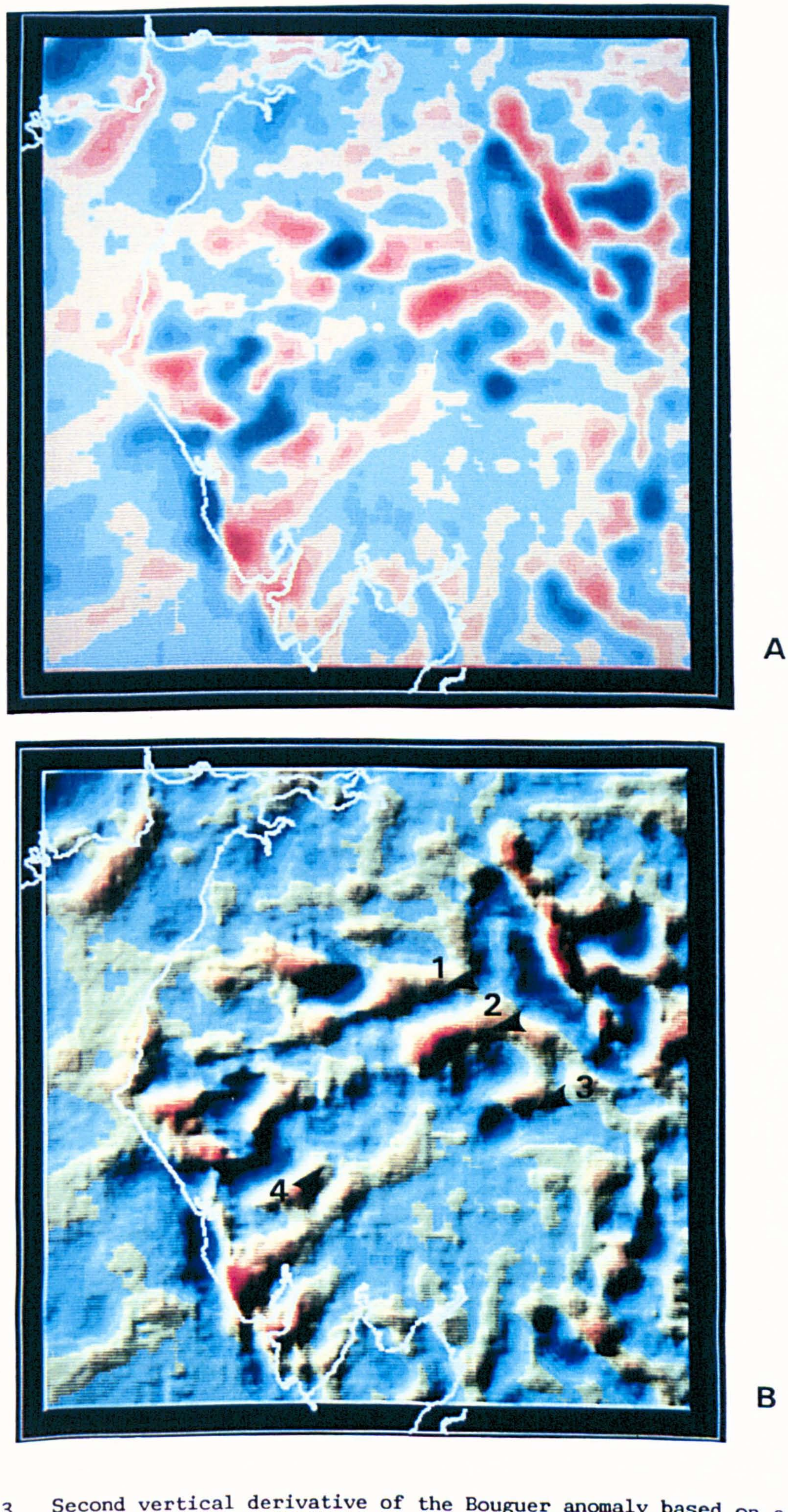


Figure 6.13 Second vertical derivative of the Bouguer anomaly based on a 2 km grid (a) flat colour image, (b) northwest-illuminated colour-shaded. Numbers indicate lineaments discussed in the text.

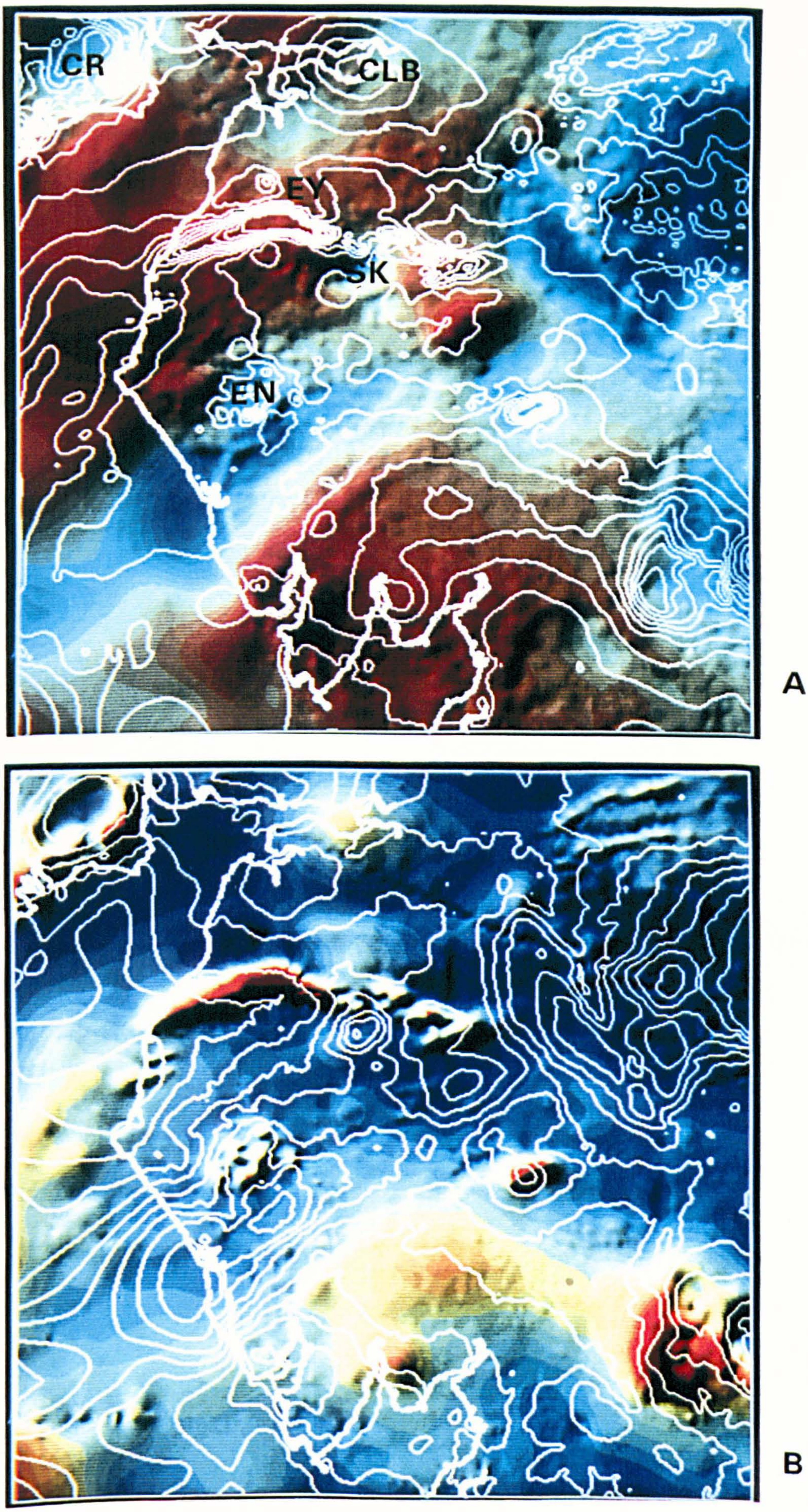


Figure 6.14 Combined images of (a) contours of the reduced-to-pole magnetic field over NW-illuminated, colour-shaded Bouguer anomaly, (b) contours of Bouguer anomaly over NW-illuminated, colour-shaded, reduced-to-pole magnetic field. CR = Criffel Granodiorite, CLB = Carlisle Basin magnetic high, EN = Ennerdale Granophyre, EY = Eycott Group, SK = Skiddaw Granite.

Figure 6.15 Combined image generated by multiplying the NW-illuminated, colour-shaded gravity second vertical derivative with the NW-shaded horizontal gradient of the reduced-to-pole magnetic field.

Figure 6.16 shows a composite image generated by adding the northwest-illuminated, colour-shaded images of the gravity and magnetic residual fields (i.e. Figures 6.9 a & b). This combines information on both anomaly amplitude and anomaly gradient from both datasets. Areas characterized by residual anomaly lows in both fields show deep blue (i.e. sedimentary basins underlain by non-magnetic basement and areas underlain by deep-seated, non-magnetic granites), and those characterized by residual anomaly highs in both fields show deep red. Lineaments that are common to both datasets are reinforced, such as lineaments 1 and 2 previously identified. However, the most interesting new feature on Figure 6.16 occurs outside the Lake District, in the northern Pennines. Lineaments associated with the Pennine Fault System appear to continue southwards across the Askrigg Block and those associated with the Dent Fault appear to extend northwards across the Alston Block, forming an X-shaped feature on the eastern side of the image. The significance of this and other features is discussed in the following section.

6.7 STRUCTURAL INTERPRETATION OF THE IMAGES

Image processing of the gravity and aeromagnetic data has revealed a number of prominent linear features and has resolved residual anomalies due to density and magnetization contrasts within the upper few kilometres of crust. In this section the information from all the images is brought together and discussed in terms of the structural history of the Lake District. The following discussion concentrates mainly on features within the Lower Palaeozoic inlier of the Lake District although some reference is made to the most prominent features in the surrounding area.

In order to correlate the information, both between the different images and with mapped geological and structural information, the most important lineaments and anomalies have been identified on the appropriate images and transcribed onto a single diagram (Figure 6.17). Residual gravity lows are defined mainly from the second derivative and 10th order residual fields (Figures 6.13 and 6.9a). The broad areas of low gravity field are defined from the 'geologically based' residual map described in Section 7.2 below (see Figure 7.2b).

A degree of subjectivity is involved in defining the exact trace of some lineaments. In a simple case, such as a linear vertical contact between two lithologies of contrasting density, the line of maximum gradient highlighted on the shaded-relief image marks the contact. However, many of the more important lineaments visible on the shaded images are related to a series of different structures developed along the same line, perhaps due the influence of a major fracture within the underlying crust. In such cases the trace of a lineament may coincide with a prominent gradient along one part of its length or with the centres of anomalies (highs or lows) along other parts. The lines shown on Figure 6.17, therefore, do not necessarily coincide with specific density or magnetization contrasts identifiable at the surface. Rather, each defines the most 'representative' trace of a lineament as discerned from the complete set of images.

Within the Lower Palaeozoic inlier of the Lake District, two sets of major geophysical lineaments are observed (Figure 6.17). The most prominent set trends in an east-northeasterly direction and possibly extends across the Vale of Eden onto the Alston Block (see below). The second (subsidiary) set has a more northeasterly trend and is apparent

Figure 6.17. (Following page)

Synthesis of information derived from the images.

Lineaments: ADL = Armathwaite Dyke, CL = Crummock, PLF = Pennine Fault Zone, SBL = Southern Borrowdales, UL = Ullswater.

Residual gravity lows attributed to granitic and/or igneous (BVG) sources: CN = Coniston, CR = Criffel, CW = Crummock, DM = Dunmail, ED = Eskdale Granodiorite, EN = Ennerdale, ES = Eskdale, HW = Haweswater, RD = Rydal, SH = Shap, SK = Skiddaw, TM = Threlkeld, UL = Ulpha, WE = Weardale, WN = Wensleydale, WS = Wasdale.

Residual gravity lows attributed to sedimentary sources: CB = Carlisle Basin (Permo-Triassic), CC = Carlisle Basin (Carboniferous), IB = Irish Sea Basin, IC = Ingleton Coalfield, UC = Upper Carboniferous, VE = Vale of Eden, WGP = Windermere Group.

Magnetic highs: AB = Askrigg Block, CLB = Carlisle Basin, CM = Cartmell, CR = Criffel Granodiorite, EN = Ennerdale Granophyre, EY = Eycott Group, SH = Shap Granite, WI = Windermere, WS = Whin Sill.

mainly across the outcrop of the Borrowdale Volcanic Group and on the western side of the Skiddaw Group outcrop. These trends presumably relate to structures developed during the closure of Iapetus and the early Devonian (Acadian) deformation. Superimposed on these is a south-southeasterly to southeasterly Permo-Triassic trend. The Pennine Fault System, which marks the eastern boundary of the Permo-Triassic half-graben of the Vale of Eden, is the most important of these structures and is characterized by a prominent SSE-trending gravity lineament. A subtle grain, with trends varying between ESE and SSE, is also apparent on some images (e.g. Figures 6.10 and 6.11) and may be related to minor structures developed during Permo-Triassic and (possibly) Tertiary times.

6.7.1 The Crummock Lineament

It is the major Caledonoid structures which are the principal focus of attention in the present study. Three prominent, ENE-trending lineaments cross the area (lineaments 1, 2 and 3, Figure 6.17). All three are related to structures observed at outcrop, but their prominent geophysical expression and their relationship with components of the concealed batholith suggest that they were important lines throughout the Lower Palaeozoic. Lineament 1, here identified as the Crummock Lineament (CL), has the strongest expression on gravity second derivative and shaded-relief images, and is visible over parts of its length on the magnetic images. It extends from Ennerdale Bridge in the west to about 2 km south of Melmerby, on the eastern side of the Vale of Eden, and possibly farther east onto the Alston Block (see Section 6.8). The line follows a major topographic low east of Keswick and is visible as a lineament on satellite imagery.

As a gravity feature the Crummock lineament is not related to any single density contrast but to a series of structures developed along the same line. Over the western part of the Skiddaw Group outcrop the line follows close to the southern side of the Crummock Water aureole, an elongate zone of bleached and indurated siltstone and mudstone approximately 24 km in length and 3 km wide (see Chapter 1). The second derivative and residual gravity fields show a residual gravity low roughly coincident with the aureole (anomaly CW Figure 6.17) which has been interpreted as an elongate, high-level granitic body (Cooper et al. 1988, see also Chapter 7 of this thesis). To the east of the Crummock aureole, the residual gravity low due to the Threlkeld Microgranite (anomaly TM) lies along the same line. To the east of the Threlkeld Microgranite, where the Lower Palaeozoic rocks are concealed beneath the Carboniferous cover, the lineament appears as a gravity gradient with high to the north and low to the south. If the same line is projected across the Vale of Eden onto the Alston Block, it roughly follows the northern margin of the northwestern cupola of the Weardale Granite (anomaly WE Figure 6.17).

As a magnetic feature, the Crummock lineament defines the southern extent of the magnetic anomalies associated with the Eycott Volcanic Group. The southernmost outcrop of the volcanics is at Eycott Hill, on the eastern edge of the Skiddaw Group inlier, and from the form of the magnetic anomaly they clearly extend eastwards at shallow depth beneath the Carboniferous cover. The magnetic anomaly fades eastwards as the Lower Palaeozoic rocks become more deeply buried beneath the Permo-Triassic sediments of the Vale of Eden but a sharp anomaly occurs along the same line at the northern end of the Cross Fell inlier (see Figure 6.9b). Volcanic rocks at this location have been attributed to the Eycott Group (Wadge 1978, Cooper and Molyneux, in press) and it therefore seems justified to extend the lineament across the Vale of Eden. Over the main Skiddaw Group outcrop, where there are no susceptibility contrasts at the surface, the lineament is only vaguely apparent as a deep-seated magnetic feature (see, for example, Figure 6.6b).

Since the Crummock lineament was first recognized as a geophysical feature (in the early phases of the present study) its geological significance has become increasingly apparent. The lineament separates two stratigraphically distinct tracts within the Skiddaw Group (see Section 1.2.1 and Figure 1.3). To the north the mudstone/siltstone sequence is folded and faulted into a series of blocks and thrust sheets, while to the south the Buttermere Formation is considered to be an olistostrome comprising the lower (Tremadoc-Arenig) part of the pile slumped and redeposited in the Llanvirn (Webb & Cooper 1988, A.H. Cooper pers. comm.). To the north of the line, slump structures are SSE-facing and to the south mainly NNW-facing. A similar stratigraphical contrast has been reported between Skiddaw Group rocks on either side of the line in the Cross Fell inlier (A.H. Cooper pers. comm.). This evidence led Webb & Cooper (1988) to suggest that the Crummock line approximates to the axis of the Skiddaw Group basin with the NNW-facing slope being the steeper. They point out that this is compatible with the development of a marginal basin along the NW edge of the Avalonian-Cadomian continental plate by listric, extensional, normal faulting of the basement downthrowing to the NNW.

Taken together, the geological and geophysical evidence suggests that the Crummock lineament was an important structural feature throughout early Ordovician to early Devonian times. Firstly, the structural evidence from the Skiddaw Group (cited above) indicates that the line was active as the axis of an extensional basin during the early Ordovician (Tremadoc/Arenig). Secondly, the line marks the southern limit of the (magnetic) Eycott Volcanic Group. It is possible that volcanic sediments in the Tarn Moor and Kirkland formations, to the south of the Crummock lineament, may equate in age with the Eycott volcanics and could come from these or another source (A.H. Cooper pers comm.) but, as far as the author is aware, no volcanic rocks to the south of the line have been correlated definitely with the Eycott Volcanic Group, either in the Lake District or the Cross Fell inlier. This would be compatible with late Llanvirn movement (vertical and/or strike-slip) along the line, possibly related to inversion of the Skiddaw Group basin during the development of the main Lake District anticline in the late Llanvirn (Webb & Cooper 1988).

Thirdly, no volcanic rocks to the north of the Crummock lineament have been correlated with the Borrowdale Volcanic Group which suggests some post-BVG (Llandeilo - Caradoc) movement. Fourthly, at least two phases of intrusive activity are associated with the Crummock lineament. These are the Threlkeld Microgranite, which lies close to the line and has been dated at 438 +/- 6 Ma (Rundle 1981) and the elongate Crummock intrusion discussed above. The bleached rocks within the Crummock aureole have been dated at 401 +/- 6 Ma (Cooper et al. 1988) which suggests that the intrusion may be associated with the early Devonian (Shap/Skiddaw) magmatism rather than the earlier Eskdale/Ennerdale intrusions. Finally, the lineament is associated with post-Crummock thrusting (i.e. the Causey Pike Thrust, A.H. Cooper pers comm.). Taken together these lines of evidence suggest a major basement fracture, perhaps initiated as an marginal fault during the development of the Skiddaw Group basin, which was reactivated during compression and acted as a focus for intrusive activity.

6.7.2 The Ullswater and Southern Borrowdales lineaments

Lineament 2, here designated the Ullswater lineament (UL Figure 6.17) lies about 8 km to the south of the Crummock lineament and is visible as a prominent feature on the gravity second derivative and residual images (Figures 6.13b and 6.9a). Like the Crummock lineament, the gravity gradients which form the Ullswater lineament are not related to a single density contrast. At its western end the line runs close to the northern margin of the Wasdale Granite (residual gravity anomaly WS, Figure 6.17) and then, eastwards, follows the northern margin of the outcrop of the Airy's Bridge Formation which marks the northern limb of the Scafell Syncline. Farther east, the line runs along the southern side of the Ullswater inlier of the Skiddaw Group which, at its eastern end, is associated with a large, ENE-trending positive residual gravity anomaly. This anomaly lies on the northern side of the gravity low due to Haweswater pluton (anomaly HW, Figure 6.17) and extends eastwards towards the Vale of Eden. There is also a hint that the same gravity gradient (i.e. high to the north of the lineament, low to the south) reappears on the western margin of the Alston Block (see Figures 6.9a and 6.13b). Magnetically, the Ullswater lineament is visible as a subtle feature over the BVG outcrop; a weak, linear residual magnetic low occuring where the Airy's Bridge formation crops out on the northern limb of the Scafell syncline (see Figure 6.9b).

The third major ENE-trending lineament lies close to the southern edge of the BVG outcrop, just south of the contact with the overlying Windermere Group sedimentary sequence (lineament 3, the Southern Borrowdales lineament, SBL in Figure 6.17). The lineament is visible mainly as a gravity feature and is related to the density contrast between the Borrowdale and Windermere groups (see Chapter 5). When projected to the east, the lineament roughly lines up with the Lunedale/Butterknowle faults on the southern margin of the Alston Block (see Section 6.8).

Skiddaw Group rocks are mostly concealed beneath younger rocks along the Ullswater and Southern Borrowdales lineaments and there is no evidence at outcrop that these lineaments are directly related to early structures within the Skiddaw Group. However, they have similar characteristics to the Crummock line in that they extend over several tens of kilometres and are related to structures of different ages along their length. It would seem likely, therefore, that like the Crummock lineament, they may represent major deep-seated fractures which have been reactivated at various times and influenced the development of the Borrowdale volcanicity and susequent granitic intrusions.

6.7.3 Other lineaments in the central and northern Lake District

The same ENE trend is apparent to the north of the Crummock lineament. Short magnetic lineaments (e.g. 11, 12 and 13, Figure 6.17) are related to outcrops of the Eycott Volcanic Group on the eastern margin of the Skiddaw Group inlier and similar anomalies occur near the coast in the west (e.g. 14, 15 and 16). The origin of the latter is unclear; they could be related to concealed Carboniferous volcanic rocks or perhaps to slices of Eycott Group lavas or magnetic basement (pre-Skiddaw Group) brought near to the surface by SSE-directed thrusts (see Chapter 7). Only weak gravity lineaments are visible over the outcrop of the Skiddaw Group north of the Crummock line; those in the west trend in a more northeasterly direction in line with the geological strike (e.g. 19 and 20). Likewise, only weak ENE trending lineaments are associated with the thickenning Carboniferous and Permo-Triassic sedimentary sequences on the northern margin of the Lake District.

Between the Ullswater and Southern Borrowdales lineaments both ENE and NE trends are apparent. Several ENE-trending lineaments relate to the Scafell Syncline and to topographic lows in the western Lake District. Magnetic lineament 5 lies on the northern limb of the syncline and correlates with the southern side of the outcrop of the Airy's Bridge Formation. Lineament 6, which has both a gravity and magnetic expression, correlates with the centre of the Scafell Syncline (at its eastern end) and passes through the contact between the Eskdale Granite and Ennerdale Granophyre. It also runs close to the line of the Wasdale valley which may partly account for the gravity expression. Lineament 7 has a gravity expression at its western end, which coincides with the Eskdale valley, and a magnetic expression at its eastern end, which corresponds to the outcrop of the Airy's Bridge Formation on the southern limb of the Scafell Syncline.

The visibility of the Airy's Bridge Formation on the magnetic images is worth noting. Magnetic susceptibility measurements on andesites from the Borrowdale Volcanic Group show a comparatively low magnetic susceptibility (0.4 to 0.6 SI*10^{-3}, Table 5.6) and it is apparent from the lack of prominent magnetic anomalies over the BVG outcrop that susceptibility contrasts between the different formations are relatively small. The existing aeromagnetic data are too widely spaced to resolve small-scale structures involving minor susceptibility contrasts but the Airy's Bridge Formation is visible, as a residual magnetic low along the limbs of the Scafell Syncline (see Figure 6.9b), presumably because the acid ignimbrites which make up the bulk of the group have a slightly lower susceptibility than the intermediate and basic lavas of the surrounding formations.

At least 3 NE-trending lineaments can be recognized on the images. The most prominent (lineament 4) appears as a gravity feature which at its NE end lies between the Scafell and Haweswater synclines and at its SW end lies close to the line of the Wrynose Anticline. Lineament 9 lies along the contact of the Borrowdale and Windermere groups in the SW Lake District and is parallel to the strike of the Black Combe Anticline. Lineament 10, a weaker gravity feature, continues NE of lineament 9 and runs parallel to the Haweswater Syncline, along its SE limb (which is also parallel to the NE part of the Nan Bield Anticline).

6.7.4 Residual gravity lows

It has been suggested above that the Crummock, and possibly the Ullswater and Southern Borrowdales lineaments are related to deep-seated fractures initiated early in the geological history of the Lake District. Within the central Lake District, the relationship between the NE- and ENE-trending lineaments and the position of residual gravity anomalies suggests that these trends affected both the evolution of the Borrowdale volcanicity and the intrusive form of the granitic batholith. The most important residual gravity lows (visible on Figures 6.9a and 6.13b) are shown on Figure 6.17. Prominent lows occur over the exposed intrusions (Shap, Skiddaw, Eskdale/Wasdale, Ennerdale and Threlkeld) and probable concealed intrusions (Haweswater and Crummock). Within the central Lake District a number of less prominent lows occur where the batholith lies concealed beneath the BVG (see Figure 6.17). The largest is designated the Dunmail low (DM). It lies between lineaments 2 and 4, and follows the axis of the concealed batholith of earlier models (see Chapter 4), coinciding approximately with the Scafell - Place Fell Syncline. The Rydal low (RD) lies between lineaments 4 and 10 on the SE side of the batholith and coincides approximately with the southwestern part of the Haweswater Syncline. A smaller low occurs to the SW of the Rydal anomaly, between lineaments 4 and 9 in the Coniston area (CN Figure 6.17). Identifiable lows also occur over the Eskdale Granodiorite (ED) and the Ulpha Syncline (UL).

The association of residual gravity lows with exposed granites suggests that the new residual lows identified in the central Lake District might also be due to separate components of the concealed batholith or separate, high level granitic intrusions. However, the spatial correlation of lows DM, RD and UL with the three major synclines in the BVG (Scafell, Haweswater and Ulpha respectively) suggests that these may be due to thick sequences of low density volcanic rocks (e.g. Airy's Bridge Formation) within the synclines. Alternative models for lows DM, RD, UL and CN are examined in Chapter 7 of this thesis. However, whether they are due to granite cupolas or to thick BVG sequences, the very existence of the anomalies and their relationship with the lineaments indicates that they represent important structures within the Lower Palaeozoic sequence of the Lake

District. The implications of the various models are discussed in Chapter 8.

6.7.5 The southern Lake District

In the southern Lake District, where the Windermere Group crops out, no strong gravity or magnetic lineaments are visible on the images. The most prominent geophysical feature in this area is the large, positive magnetic anomaly which forms part of a broad belt of anomalies extending from East Anglia, via the Lake District, to the Isle of Man. Two distinct magnetic highs occur in the southern Lake District, near Windermere and Cartmel (anomalies WI and CM respectively, Figure 6.17). Between the two is a distinct residual gravity low (Figure 6.9a and gravity anomaly WGP on Figure 6.17). If, as the long wavelength of the magnetic anomalies suggests, the magnetic rocks are deeper than the base of the Windermere Group, then the residual gravity low probably approximates to the deepest parts of the Silurian basin. The regional significance of the magnetic belt is discussed in Section 6.8 and models of this area are given in Chapter 7.

6.7.6 Features peripheral to the Lake District

Although anomalies within the Lake District itself are the main focus of the present study, a number of features in the surrounding area deserve mention. On the eastern edge of the images, large gravity lows are associated with the Lower-Devonian Weardale and Wensleydale granites, beneath the Alston and Askrigg blocks respectively, and individual cupolas are resolved on the residual gravity image (anomalies WE and WN Figure 6.17). The Pennine Fault System is characterized by a prominent gravity lineament (22 Figure 6.17) due to the large contrast between the Lower Palaeozoic rocks in the Cross Fell inlier and the thick, low-density, Permo-Triassic sedimentary sequence in the Vale of Eden (anomaly VE Figure 6.17). The Alston Block itself is characterized by a mass of short wavelength magnetic anomalies where the Carboniferous Whin Sill lies close to the surface (see for example Figure 6.11a). Within this area subtle ENE and ESE trends can be observed which presumably relate to faults affecting the sill. Strong magnetic lineaments are observed where the Whin Sill crops out on the northern margin of the Alston Block (lineaments 23, 24 and 25 Figure 6.17).

The most prominent gravity and magnetic anomalies on the western margin of the Askrigg Block lie not along the Dent Fault, but along a broad NNW-trending zone some 8 km to the east (lineament 26), where Lower Palaeozoic rocks of above average density and susceptibility come close to the surface along the western margin of the Wensleydale Granite (Bott 1967, Wilson & Cornwell 1982). The Craven Fault, on the SW margin of the Askrigg Block, is visible as a prominent linear feature on the gravity images (lineament 27 Figure 6.17) especially where the low density Westphalian rocks of the Ingleton Coalfield lie to the SW of the fault (anomaly IC, Figure 6.17).

An interesting feature of the images over the Alston and Askrigg blocks is the presence of the two broad lineaments labelled 28 and 29 on Figure 6.17. Neither feature is particularly obvious on individual gravity and magnetic images but they appear very prominently on the composite colour-shaded gravity/magnetic image (Figure 6.16). Whether these broad linear features have any geological significance is open to question but they do invite speculation. Lineament 28 runs a few

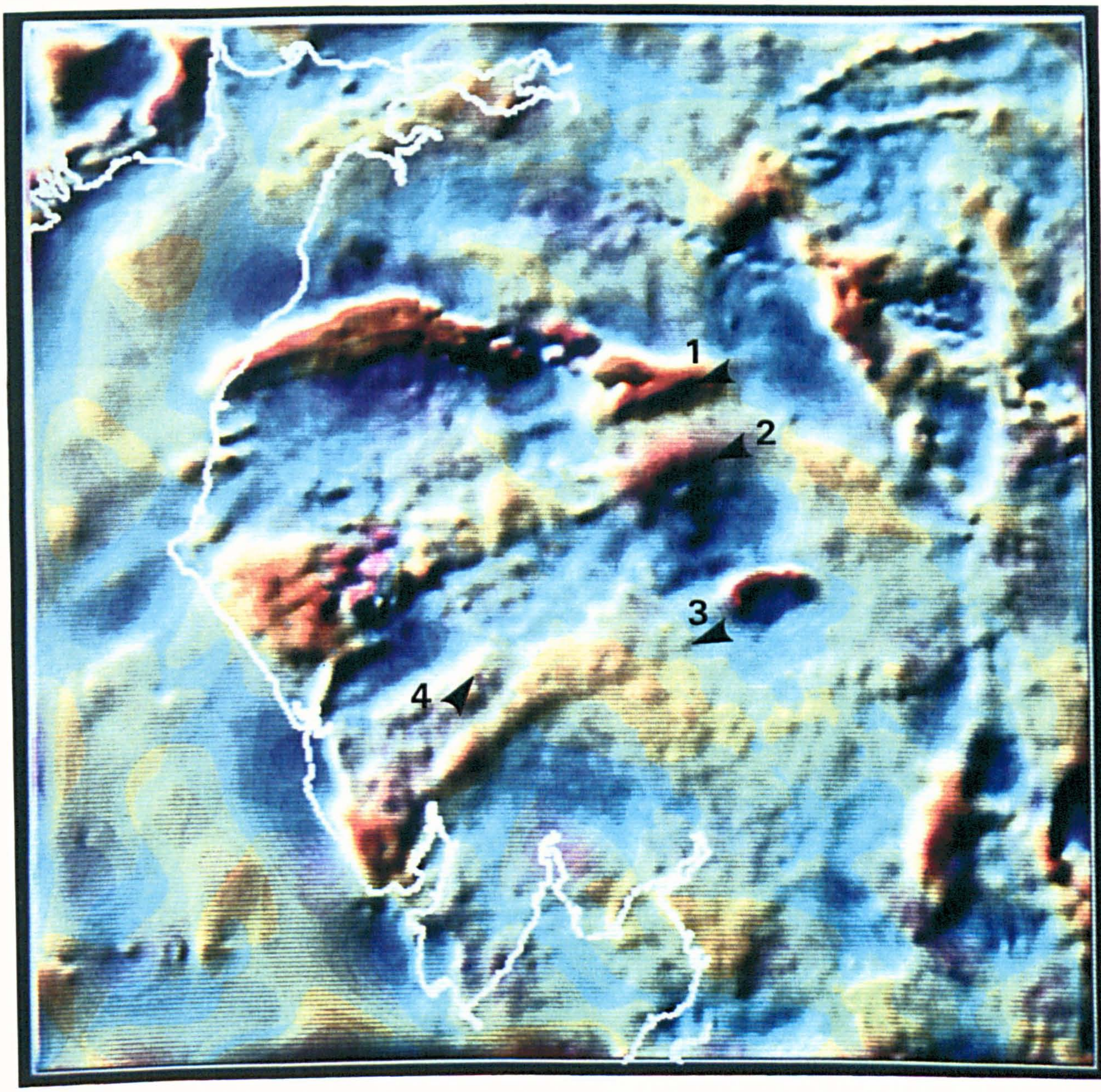
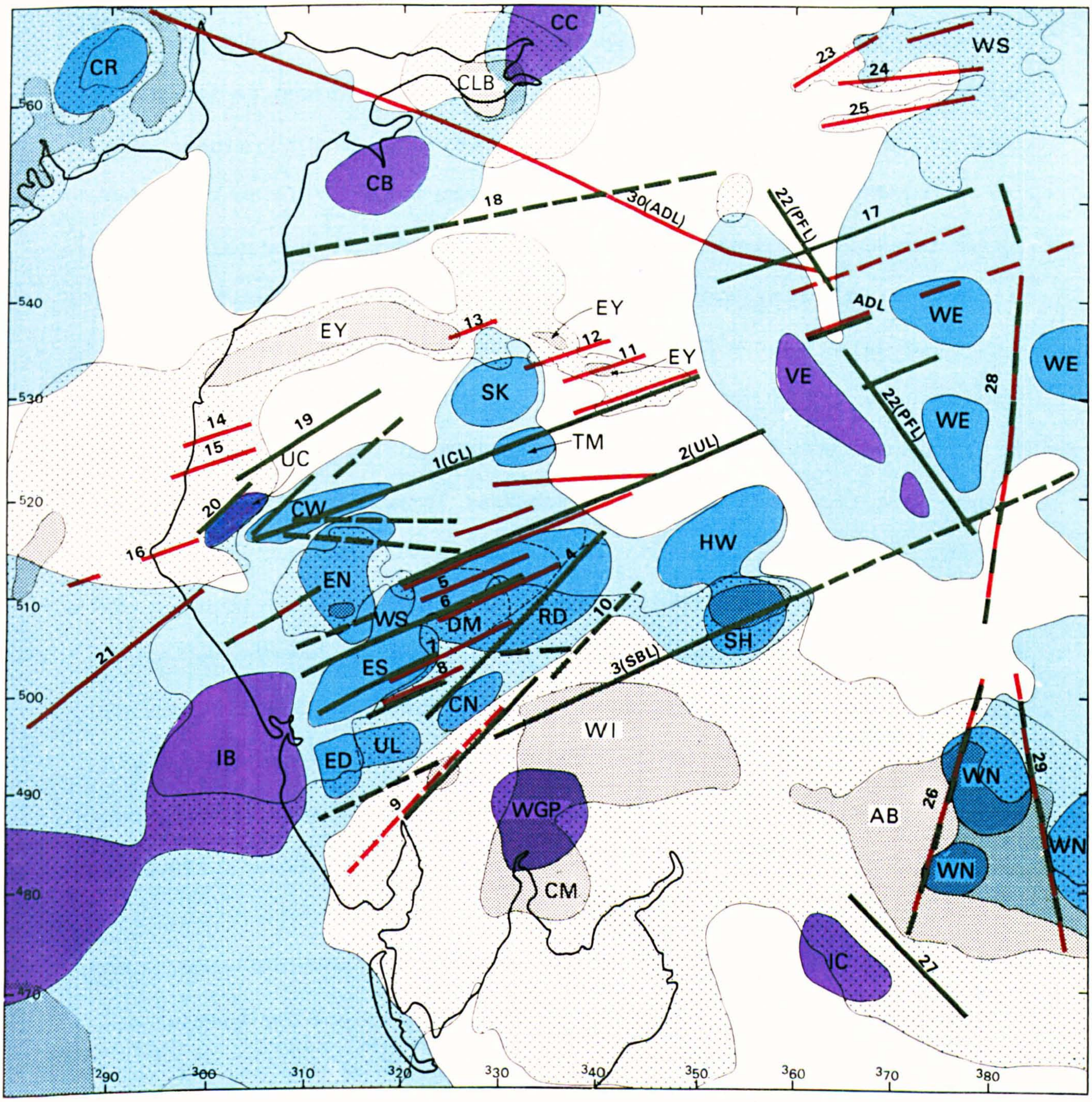


Figure 6.16 Combined image generated by adding the NW-illuminated, colour-shaded images of residual gravity and reduced-to-pole magnetic fields. Numbers indicate lineaments discussed in the text.



Closed gravity lows associated with sedimentary sequences

Local residual gravity lows associated with granitic intrusions. Indentified from processed images of the gravity field.

Broad areas of low gravity associated with low-density granitic intrusions and Carboniferous to Permo-Triassic sedimentary rocks (residual field <-15mGal, see text)

Aeromagnetic anomaly >+20nT

Aeromagnetic anomaly > -50nT

(from magnetic field reduced to pole)

Gravity lineament

Magnetic lineament

(Pecked lines indicate weaker lineaments)

Figure 6.17

kilometres west of the Burtreeford Disturbance and could be viewed as the northward continuation of lineament 26. More speculatively, lineament 29 could be linked to the Pennine Fault System, albeit with a more southerly trend. In a recent study of the Dent Fault System, Underhill et al. (1988) suggested that it may have been initiated as an early Palaeozoic structure, reactivated during Carboniferous and early Permian time. They suggested that it may have acted as a dextral oblique- or strike-slip zone during N-S crustal extension in the early Carboniferous and that sinistral movement occured during the Variscan orogeny due to NW-SE compression. It seems possible that lineament 28 might represent a line of weakness across the Alston Block, between cupolas of the Early Devonian Weardale Granite, along which some of this strike-slip movement was accommodated. Likewise, lineament 29 could be related to the Pennine Fault System in the same way. Any further comment on these features, and others over the Alston and Askrigg Blocks, must await a thorough analysis of images to the east of the present area which is being carried out by others as part of a separate project.

Three features to the north of the Lake District are enhanced by the imagery and worthy of mention. Firstly, the large positive magnetic high in the Carlisle Basin (CL Figure 6.17) is associated with a relatively positive gravity ridge between two gravity lows (CB and CC, Figure 6.17) which are related to Permo-Triassic and Carboniferous depocentres respectively (Abbot 1987). The cause of the magnetic anomaly is unknown but its relatively long wavelength and association with a gravity high suggest the presence of a basic intrusion beneath the Carboniferous (see models in Chapter 7). Secondly, the track of the Tertiary Armathwaite dyke is particularly well diplayed on the shaded magnetic images (e.g. Figure 6.9b, lineament 30 on Figure 6.17). Finally, the images are particularly effective for displaying the relationship between the gravity and magnetic anomalies over the Criffel Granodiorite in the NW corner of the area. The low-density and relatively non-magnetic central part of the intrusion is characterized by a major gravity low (gravity anomaly CR, Figure 6.17) while an annular magnetic anomaly occurs over marginal (more mafic) phases of the intrusion.

6.8 REGIONAL TRENDS

Images of the gravity and magnetic data over a wider region have been created in order to examine structural trends throughout England, Wales and southern Scotland. Colour-shaded images of northern England, based on data gridded at 0.5 km, are shown in Figures 6.18 (gravity) and 6.19 (magnetic). Gravity and magnetic images of the whole of central Britain, based on data gridded at 1.2 km, are shown in Figures 6.20 and 6.21 respectively. The images were created using the same processes as described above for the Lake District except that illumination from the north was used as this was found to be more effective for emphasizing both the NW-SE and NE-SW trends that occur in central areas.

These images have been analysed in detail as part of a separate study by the present author in collaboration with N.J Soper and T.C Pharaoh (Lee et al. in press). The interpretation diagram from the paper is reproduced here as Figure 6.22 and the discussion below is based on that given in the paper (with some further additions by the present author). Only points relevant to the Lake District region are included.

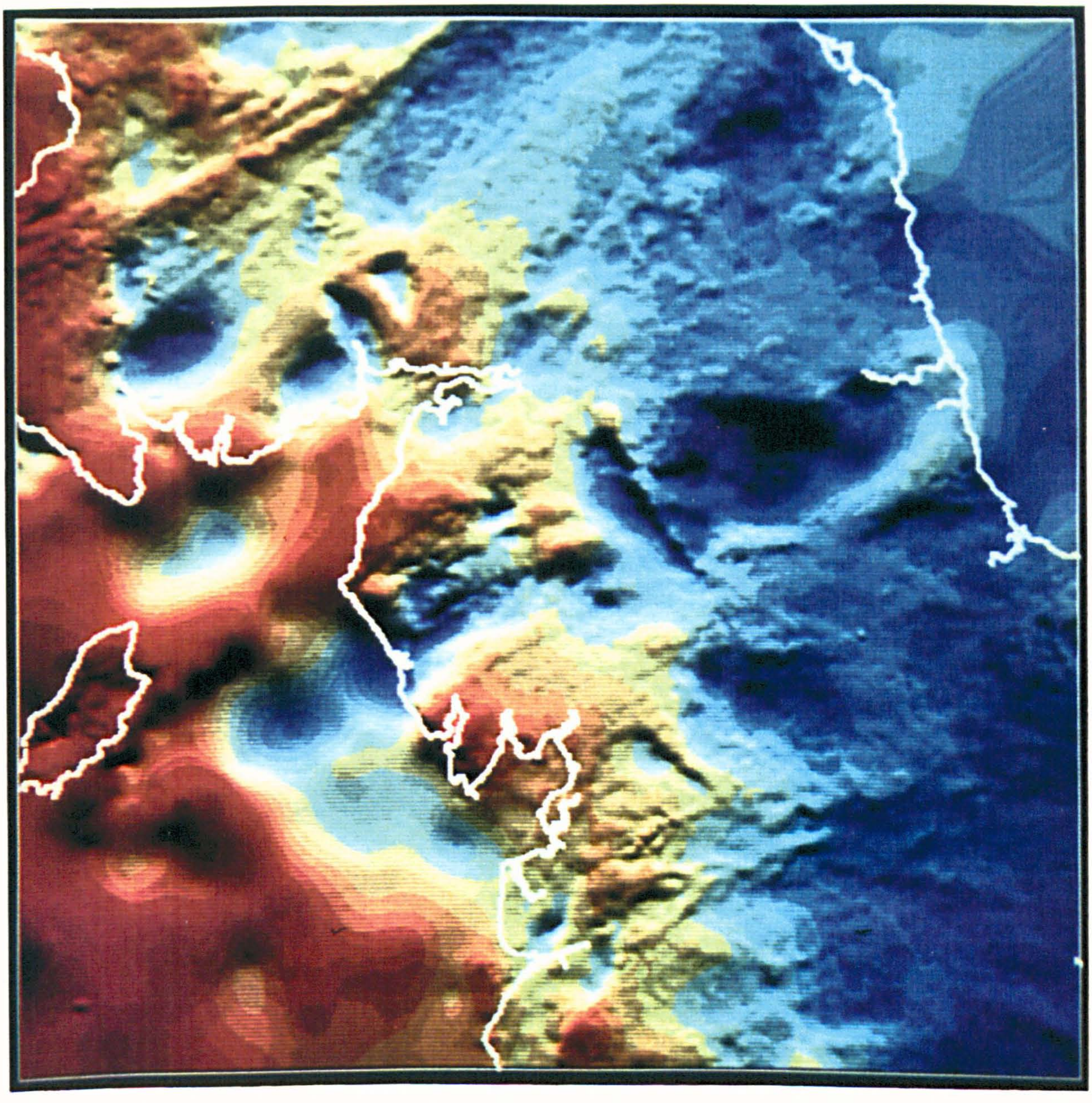


Figure 6.18 North-illuminated, colour-shaded image of Bouguer anomaly for northern England. Bouguer reduction density = 2.70 Mg/m^3. Grid size = 0.5 km.

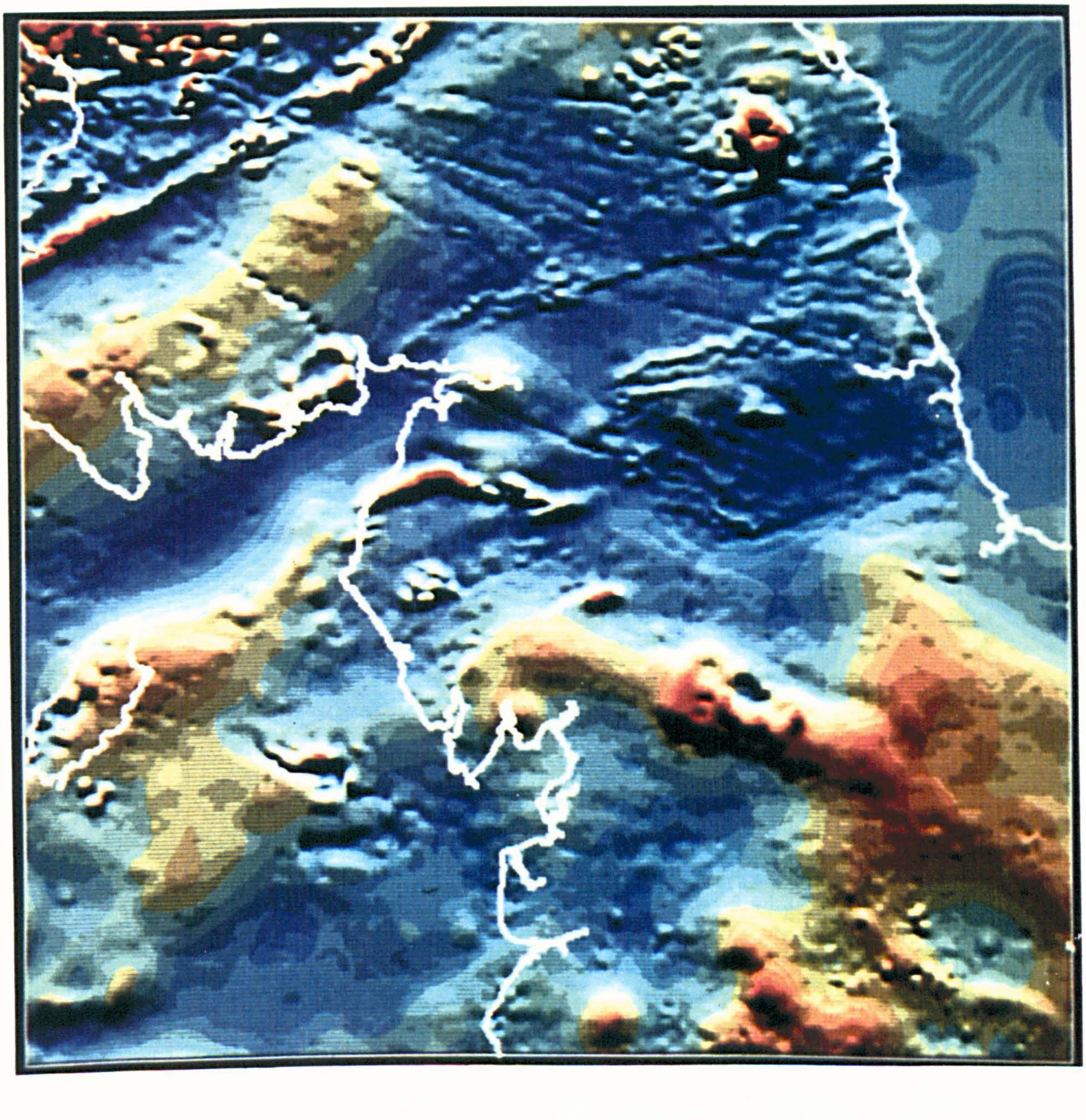


Figure 6.19 North-illuminated, colour-shaded image of aeromagnetic anomaly (reduced to pole) for northern England. Grid size = 0.5 km.

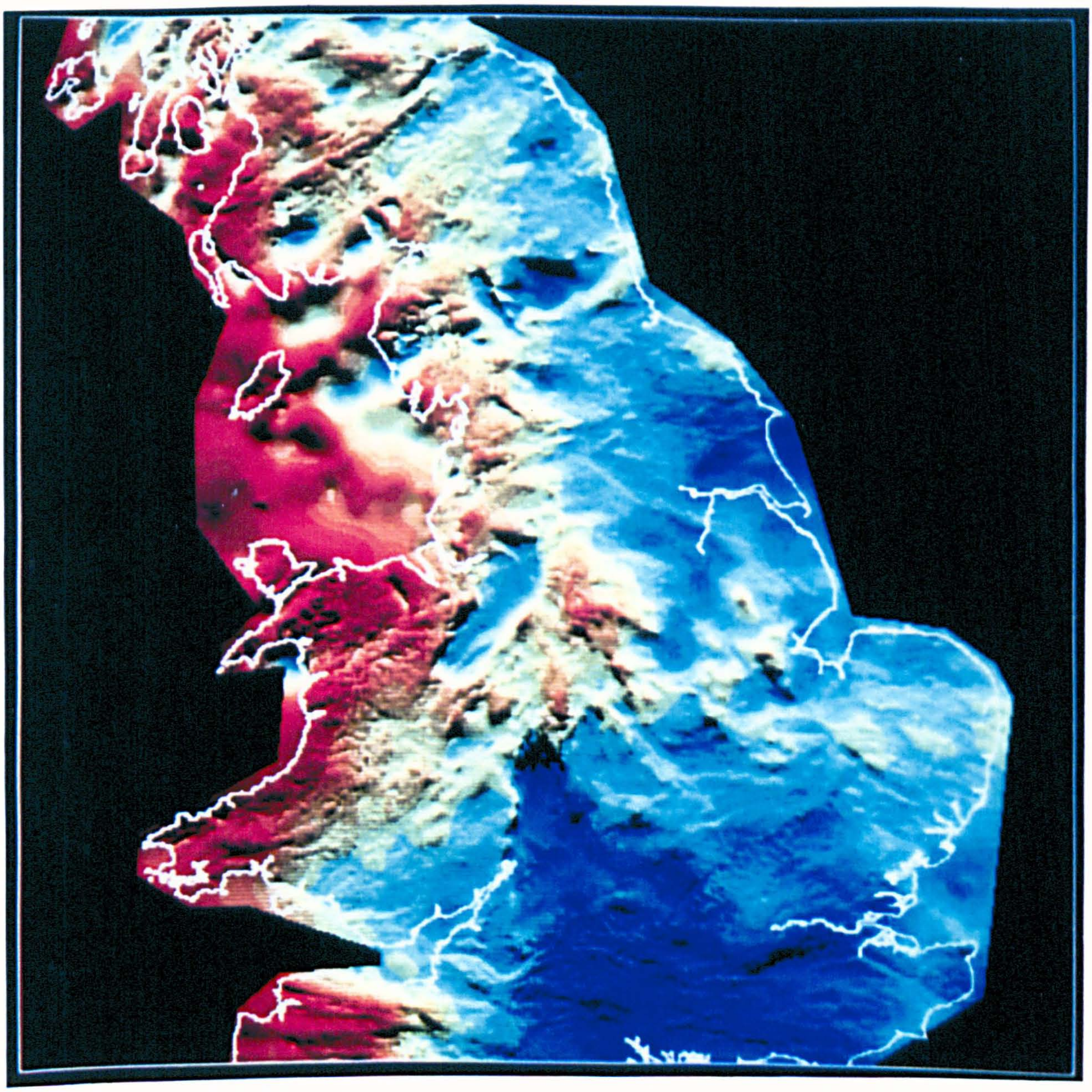


Figure 6.20 North-illuminated, colour-shaded image of Bouguer anomaly for central Britain. Bouguer reduction density = 2.65 Mg/m^3. Grid size = 1.2 km.

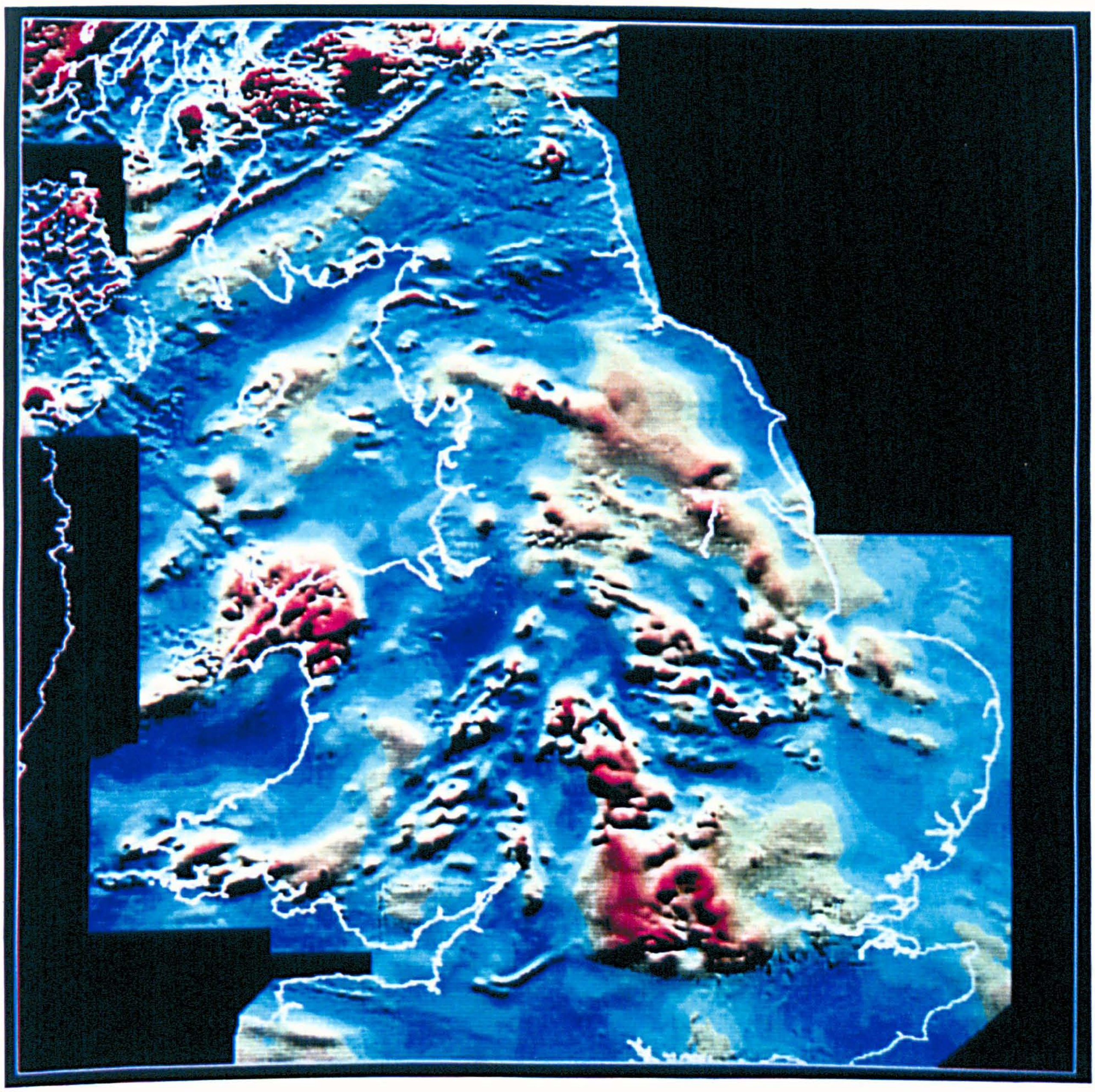


Figure 6.21 North-illuminated, colour-shaded image of aeromagnetic anomaly for central Britain. Grid size = 1.2 km.

Figure 6.22 Synthesis of information derived from images of central Britain (from Lee et al. in press). Light stippling defines broad areas of positive (reduced to pole) magnetic field which generally indicates the presence of buried magnetic rocks. Dark stippling defines areas of higher (>80nT) magnetic field which generally indicates the presence of near-surface magnetic basement or magnetic volcanic rocks. Hatched pattern defines prominent gravity anomalies. Lineaments are numbered and given a suffix G (gravity only), M (magnetic only) or GM (gravity and magnetic). Magnetic highs and gravity anomalies discussed in the text are identified by the letters MH and GA respectively.

The Crummock, Ullswater and Southern Borrowdales lineaments, identified in the previous section, are visible on the images of northern England (Figures 6.18 and 6.19) and, to a lesser extent, on figures 6.20 and 6.21. The reduction in clarity of these features is due in part to the use of a larger gridding interval (see above) and, in the case of the gravity images, to the use of a lower density for the Bouguer corrections (2.70 and 2.65 Mg/m^3 for figures 6.18 and 6.20 respectively) compared with the value of 2.75 Mg/m^3 considered appropriate for the Lake District. Nevertheless, the images illustrate the general ENE trends along the northern and southern margins of the Alston and Lake District 'blocks' (e.g. the Southern Borrowdales lineament and the southern margin of the Alston Block), and there is even a suggestion that the Crummock lineament may project eastwards across the Alston Block to line up with the Ninety Fathom Fault.

On a broad scale (Figures 6.20 to 6.22) the pattern of anomalies and trends emphasizes the observation of Soper et al. (1987b) that late Caledonian structure to the south of the Solway line is arcuate, the arc marking a change from a NE-SW Appalachian trend in the west to a NW-SE Tornquist trend in the east. The magnetic images in particular give the impression of structures moulded around the northern flank of the Midlands Microcraton which Soper et al. (1987b) suggest acted as a 'rigid indenter' during the final (early Devonian) closure of Iapetus, moving northwards into an embayment formed by the earlier suturing of Laurentia and Baltica (see discussion in Section 1.3). The pattern of magnetic anomalies over central England seems to define the extent of the Midlands Microcraton and delineate crustal elements and characterisic trends within it. Magnetic lineaments and the grain of gravity anomalies, trending in northeasterly and northwesterly directions on either side of the microcraton, seem to relate to the evolution of the Welsh and eastern English Caledonides respectively. North of the Solway line, lineaments related to the pre-Devonian structures trend predominantly NE or ENE and are related to terrane accretion events on the northern margin of Iapetus and eventual closure across the main Iapetus convergence zone (see Section 1.3).

The most important regional-scale anomaly relevant to the Lake District is the prominent belt of magnetic anomalies extending through eastern and northern England, as described by Bullerwell (in Bott 1961) and designated magnetic ridge 1 by Wills (1978). The belt extends in a NW direction from East Anglia (magnetic high MH6, Figure 6.22), where it is associated with postulated concealed granites around The Wash (Allsop 1987; gravity anomalies GA3 and GA4 Figure 6.22), towards the postulated Market Weighton Granite (Bott et al. 1978; magnetic high MH7 and gravity low GA5). It then turns WNW to link up with magnetic anomalies related to the concealed granite at Wensleydale (Bott 1967, Wilson & Cornwell 1982; magnetic high MH8 and gravity low GA6). The magnetic images (Figures 6.19 and 6.21) suggest that this feature forms two parallel strands in northern England. One trends north-westwards from Market Weighton (MH7) to the Wensleydale Granite (MH8) and southern Lake District (MH9), then turns east-southeastwards to south of the Isle of Man (MH10). The other strand, approximately 50km to the north, defines the northern edge of the belt. It is less well defined in northeast England (MH11) but appears to trend towards the northern Lake District, where it is interrupted by the sharp arcuate high across the Eycott Volcanic Group (MH12). It then, more prominently, turns ESE towards the Isle of Man (MH13) where it coincides with a gravity high along the Ramsey - Whitehaven ridge between the Solway and Irish Sea basins. The Lake District batholith lies between these strands.

The source of the magnetic anomalies and the significance of the NW trend in Eastern England have been the subjects of considerable discussion. The anomalies originate at a depth greater than the top of the pre-Devonian rocks (Bott et al. 1978) and have been used to infer the northern extent of shallow Proterozoic rocks of the Midlands Microcraton (Wills 1978, Dunning 1985). However, the northern margin of the craton has recently been defined on other grounds (Pharaoh et al. 1987) and lies well to the south. The annular magnetic highs, associated with the Wensleydale and postulated Market Weighton granites have been ascribed to upwarping of the magnetic basement and punching through of the less magnetic granites, plus contact metamorphism of the Lower Palaeozoic country rocks (Bott 1961 and 1967; Bott et al. 1978). Likewise Allsop (1987) has suggested a similar origin for the gravity and magnetic anomalies around The Wash.

The high surrounding the Wensleydale Granite (MH8) was drilled at Beckermonds Scar and found to result from early Ordovician siltstones and greywacke sandstones with a high magnetite content. This was believed by Berridge (1982) to be detrital, but as pointed out by Cann (in discussion of that paper) was clearly recrystallised during the contact alteration of the sediments. Greywackes at outcrop in the Lake District (and perhaps at Ingleton), of similar age to those at Beckermonds Scar, are not strongly magnetic and this might suggest that the magnetite at Beckermonds Scar is mainly of contact origin. However, the fact that other granites intruded into similar rocks (e.g. the Weardale and Lake District granites) have no prominent marginal anomalies, plus the persistence of the magnetic belt as a deep-seated anomaly between the known granites suggests that contact metamorphism is not the only cause. Two possibilities are that the broad magnetic anomaly (or parallel belts of anomalies) represents either (a) belts of buried early Palaeozoic (Cambrian?) sedimentary rock with a higher primary magnetite content than most of the later (Ordovician) sediments such as the Skiddaw Slates, or (b) a zone in which a higher grade of regional metamorphism resulted in the formation of magnetite within the Lower Palaeozoic succession. The present pattern of magnetic anomalies would then be consistent with a belt of later granitic intrusions, referred to above, having uplifted, punched through and altered these rocks.

The possibility that the Lower Palaeozoic succession within the magnetic belt differs in character from that surrounding it is supported by the observations of Brown et al. (1987) concerning the contrasts between the Weardale and Wensleydale granites, which lie, respectively, to the north of and within the belt. They pointed out that in terms of magma provenance, Nb-Y discriminant diagrams place the former in a 'volcanic arc' setting and the latter just inside the 'within-plate' field. In terms of crustal setting the Weardale Granite was emplaced into a predominantly hydrous greywacke-shale sequence at or below greenschist-facies metamorphic grade and the Wensleydale Granite was emplaced into relatively anhydrous siltstones-sandstones.

A further point of interest regarding the trend of the magnetic belts is whether the SE-trending limb in NE England and the WSW trending limb in the Irish Sea represent: (a) a single arcuate structure moulded round the outer margins of the Midlands Microcraton;

(b) two distinct trends intersecting in the vicinity of the Lake District; or (c) an early trend cross-cut by a later one.

It is possible to envisage that the crust which now lies on the western and eastern sides of the Midlands Microcraton developed separately, related to closure of the Iapetus and Tornquist oceans respectively, with subsequent convergence of the trends in northern England as both oceans narrowed. This scenario would imply a contrast in the lower crust, on the southern side of the Solway line, between western and eastern England. There is some tentative evidence for this. For example, Bott et al. (1985), in discussion of their seismic refraction line across northern England, noted that the base of the layer identified as 'southern' continental crystalline basement was well defined at a depth of about 16 km beneath the North Sea and Northumberland Trough but its base is undetermined beneath the Irish Sea. They also noted a difference in the character of the Moho between the North Sea (relativly sharp) and the Irish Sea (gradational) and tentatively suggested that this might indicate the juxtaposition of different crustal types along strike to the south of the suture.

However, there is also some evidence that the ENE trend, most prominent in the Irish Sea, cuts across the SE trend in northern England, rather than intersecting with it or gradually swinging round to a more south-easterly trend. For example, the Crummock, Ullswater and Southern Borrowdales lineaments can be extended tentatively onto the Alston Block and the Crummock and Southern Borrowdales lines possibly correlated with the fault systems along the northern and southern margins of the block respectively. Moreover, Freeman et al. (1988) have correlated a crustal block immediately to the south of the

Iapetus Suture on line NEC with the Lake District (zone C, Figure 1.15, see discussion in Section 1.4). If Lake District type lower crust lying immediately to the south of a north-dipping suture does in fact extend from the Irish Sea to the North Sea, this would imply that the south-easterly trending structures related to Tornquist closure do not extend farther north than the southern margin of the Lake District and Alston Blocks. This would be consistent with a scenario in which the Tornquist Sea was closed by the Silurian (Cocks & Fortey 1982, McKerrow 1988, McKerrow & Soper 1989) while northward subduction continued for a little longer along the ENE-trending Iapetus Suture, followed by northwards underthrusting of southern 'continental' crust beneath the northern continental margin continuing until the Emsian (Soper et al. 1987b, McKerrow & Soper 1989), thus overprinting the earlier SE-trending structures. Equally, a 'Lake District terrane' (i.e. the Isle of Man, Lake District and Alston Block) may have been emplaced by strike-slip subsequent to Tornquist closure.

CHAPTER 7

DETAILED GRAVITY AND MAGNETIC MODELLING

The broad-scale, three-dimensional structure of the Lake District region has become reasonably well understood from the work of Bott (1974 & 1978) and the generalized 3-D model described in Chapter 4 of this thesis (Lee 1984a & 1986). However, this earlier gravity modelling was based on relatively simplified assumptions of the density distribution and was carried out without the control provided by the modern geological mapping (Chapter 1). Moreover, consideration of the magnetic data was not included. This Chapter describes detailed joint gravity/ magnetic modelling based on the improved gravity coverage provided by the detailed surveys in the western Lake District (Chapter 2) and the improved physical property database (Chapter 5), together with the tighter geological control provided by the recent mapping (Chapter 1) and the additional structural insight provided by the image analysis (Chapter 6).

7.1 MODELLING METHODS

The present generation of gravity and magnetic modelling software offers either 3-D interpretation of relatively simple structures or 2.5D modelling (i.e. 2-D with finite strike length) of more complex situations. Although many of the important structures in the Lake District are far from two-dimensional, it was felt that the principal requirement was for detailed, joint gravity/magnetic modelling of complex structures involving multiple density and susceptibility contrasts. The approach, therefore, has been to carry out detailed 2.5D interpretations along a series of profiles designed to investigate the form of the various components of the granitic batholith and other important aspects of upper crustal structure. The modelling was carried out using program GRAVMAG on the VAX8600 computer at Keyworth. GRAVMAG was developed at BGS by J. Busby (1986), originally for use on a PERQ workstation, and was further enhanced and implemented on the VAX by Z.K. Dabek. It is a highly interactive, graphics-orientated program for joint 2.5D gravity/magnetic interpretation which enables complex structures to be interactively created and edited on-screen.

The profile locations are shown in Figure 7.1. Lines AB, CD, EF, GH and KL run approximately perpendicular to the Caledonoid (ENE) strike of Lower Palaeozoic structures and were designed to investigate the upper crustal structure, from the southern edge of the Southern Uplands to south of the Lake District, as well as detailed structures within the Lake District itself. Both the gravity and magnetic fields were modelled together for these lines (i.e. a single model was devised to fit both fields). Profiles QR, WX and YZ are somewhat shorter and were designed specifically to investigate structures within the Lake District using the gravity data only. Profile IJ runs along the Caledonian strike from the Irish Sea to the Weardale Granite. Profiles T3, T4/8 and T11 lie along detailed gravity traverses 3, 4+8 and 11 respectively. Some of the profiles incorporate changes of direction along their length in order to traverse the centres of specific anomalies and/or cross perpendicular to the local strike. Although, strictly speaking, this violates the principles of 2.5D interpretion it is generally considered to be acceptable practice given that the geological structures involved are themselves not two-dimensional.

For lines AB to YZ the observed Bouguer gravity and (where necessary) magnetic anomaly values at 0.5 km spacing were derived from

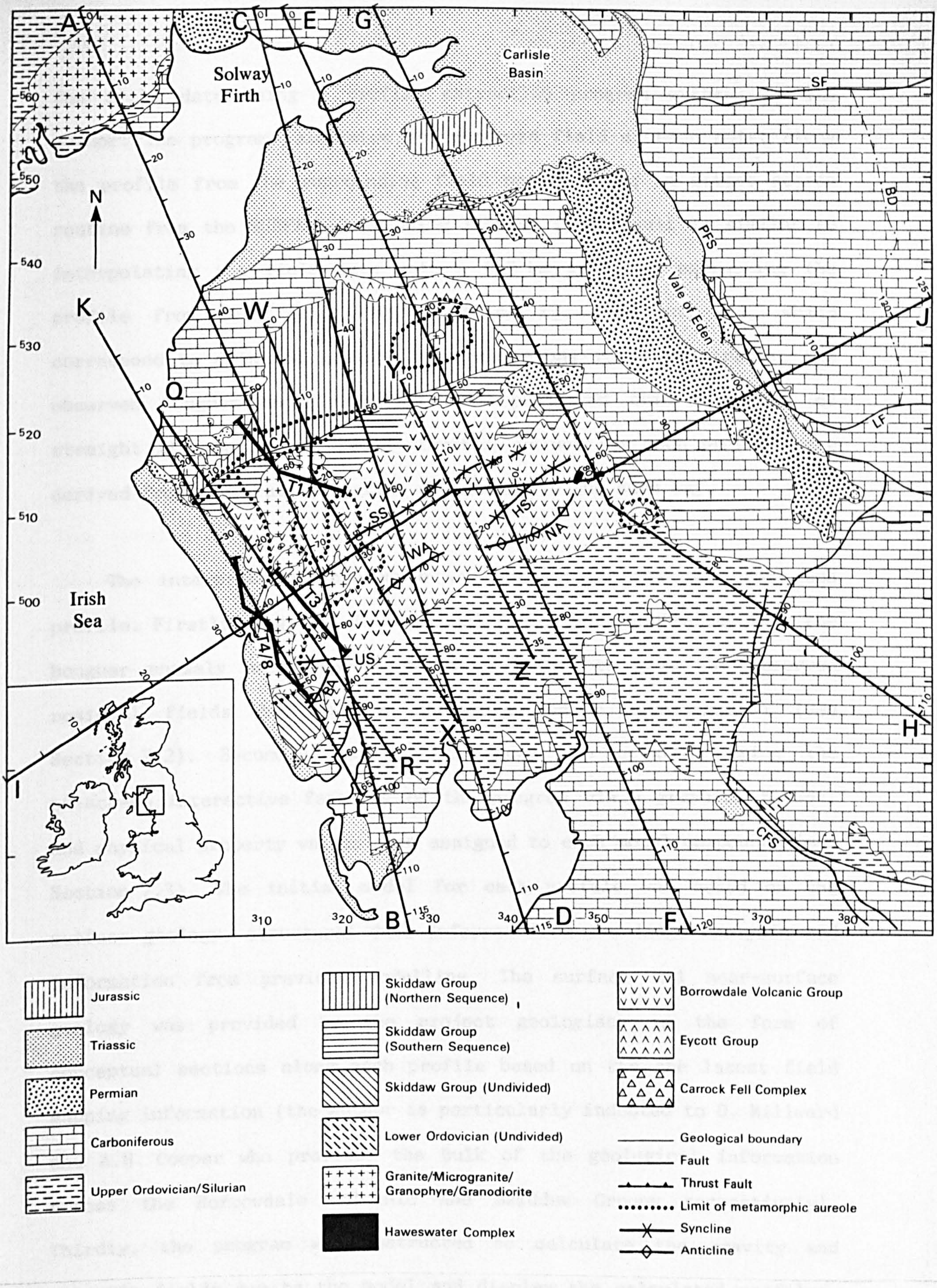


Figure 7.1 Location of interpretation profiles. Refer to geological maps for names of faults, synclines and anticlines.

the field data using a profile extraction program written by the author. The program calculates the observed field at each point along the profile from the surrounding field points using an octant search routine from the SURFACE-2 gridding library (the result is similar to interpolating the field data onto a 0.5 km grid and extracting the profile from that grid). For profiles T3, T4/8 and T11, which correspond to detailed gravity traverses along roads and tracks, the observed Bouguer anomaly values were projected onto a series of straight line segments. Ground elevation values for each profile were derived from the gravity station elevations in the same way.

The interpretation procedure was essentially the same for each profile. Firstly, regional (background) fields were subtracted from the Bouguer anomaly and observed magnetic fields to give the observed residual fields due to the structures under investigation (see Section 7.2). Secondly, an initial model was created, using the on-screen interactive features of the program via a graphics tablet, and physical property values were assigned to each model component (see Section 7.3). The initial model for each profile was based on the surface geology, structural data inferred from the image analysis and information from previous modelling. The surface and near-surface geology was provided by the project geologists in the form of conceptual sections along each profile based on the the latest field mapping information (the author is particularly indebted to D. Millward and A.H. Cooper who provided the bulk of the geological information across the Borrowdale Volcanic and Skiddaw Groups respectively). Thirdly, the program was instructed to calculate the gravity and magnetic fields due to the model and display the calculated profiles.

Finally, the model was interactively edited and refined until an acceptable fit to the observed fields was obtained.

The interactive capabilities of the program allowed various hypothesis to be tested and alternative models to be created for each profile. Theoretically, an infinite number of models could be devised to fit the observed data. The possible alternatives are constrained by the geological control, the measured physical property data and the joint interpretation of gravity and magnetic data (i.e. the magnetic data constrain the number of possible solutions to the gravity data and vice versa). The models shown in Sections 7.4 to 7.10 represent the interpretations along each profile which are felt to be the most consistent with the available geological information whilst also maintaining consistency between adjacent profiles. The interpretations are built on a number of assumptions regarding the value of the background fields and the nature of physical property contrasts at depth which are explained below. It is not possible to show the full range of alternative models, only those which are considered to be geologically realistic and significant are discussed.

7.2 REGIONAL FIELDS

In order to interpret gravity and magnetic data, anomalies due to the structures under investigation must first be isolated from regional trends and the influence of any adjacent bodies not included in the models. The calculation of the correct regional (i.e. background) gravity and magnetic fields is, therefore, critical to the validity of the interpretation. These 'geologically-based' background fields are not to be confused with the 10th order polynomial surfaces described in Section 6.5.1, which were designed primarily to separate the long and short wavelength components of the observed fields for subsequent image analysis.

In the case of gravity interpretations over large areas the usual convention is to model all positive and negative density contrasts against the density of the 'basement'. In the case of the Lake District, the oldest rocks at outcrop are the Lower Ordovician Skiddaw Group rocks. These form the core of the Lake District anticline and their base is nowhere seen. Rocks of similar age occur in Cross Fell and other inliers throughout northern England and also in the Isle of Man. In line with previous interpretations, therefore, the Skiddaw Group has been adopted as the 'basement' for the present study. All structures were modelled against their calculated representative density of 2.78 Mg/m^3 (see Section 5.6), and the observed Bouguer anomaly values were recalculated using this density for the Bouguer and terrain corrections. The background gravity field for the interpretation is thus defined as the Bouguer anomaly field that would exist if all later intrusive, extrusive and sedimentary rocks were replaced by Skiddaw Group rocks to the surface. Such a background field should contain only long wavelength components related to density variations in the mid and lower crust and regional differences in crustal thickness.

Estimating the value of the background gravity field across the area covered by the profiles is particularly problematical because, where Skiddaw Group rocks are exposed at outcrop, the Bouguer anomaly values are effected by underlying or adjacent granites. Elsewhere, where they lie concealed beneath Silurian, Carboniferous and Permo-Triassic sedimentary rocks, there is limited borehole control from which to calculate the gravity effect of the overlying sequences. An iterative approach to estimating the regional gravity field was therefore adopted. The regional field used for the earlier three-dimensional interpretation (Chapter 4) was taken as the starting point. This was a planar background field decreasing towards the east from the Irish Sea regional high (e.g. 44 mGal over the Isle of Man) which Bott (1964) interpreted as being caused by either thinner or denser crust beneath the Irish Sea region. This initial background field was subtracted from each profile to give an 'observed residual' field against which initial models were tested.

By this process it became clear that the assumed background field was incorrect in certain areas where borehole or seismic data were available to constrain the models (i.e. in the Carlisle Basin, see below) or where unrealistic thicknesses of Silurian, Carboniferous or Permo-Triassic sediments would be required to fit the residual anomalies. The background gravity field was therefore progressively modified until an acceptable fit at the available structural control points was achieved. The field finally adopted is shown in Figure 7.2 and the corresponding residual gravity field (i.e. the observed minus the regional field) is shown in Figure 7.3. The regional field decreases east-northeastwards from 38 mGal in the SW corner of the area to a low point of 15 mGal on the eastern margin of the Alston Block and then gradually increases again to the ENE. Although the process of deriving the background field is somewhat subjective, the present estimate is considered to be a significant improvement on that used for the previous 3-D interpretation and is consistent with other recent estimates of the regional field over northern England (e.g. Evans et al. 1988). The overall pattern of a broad regional low over northern

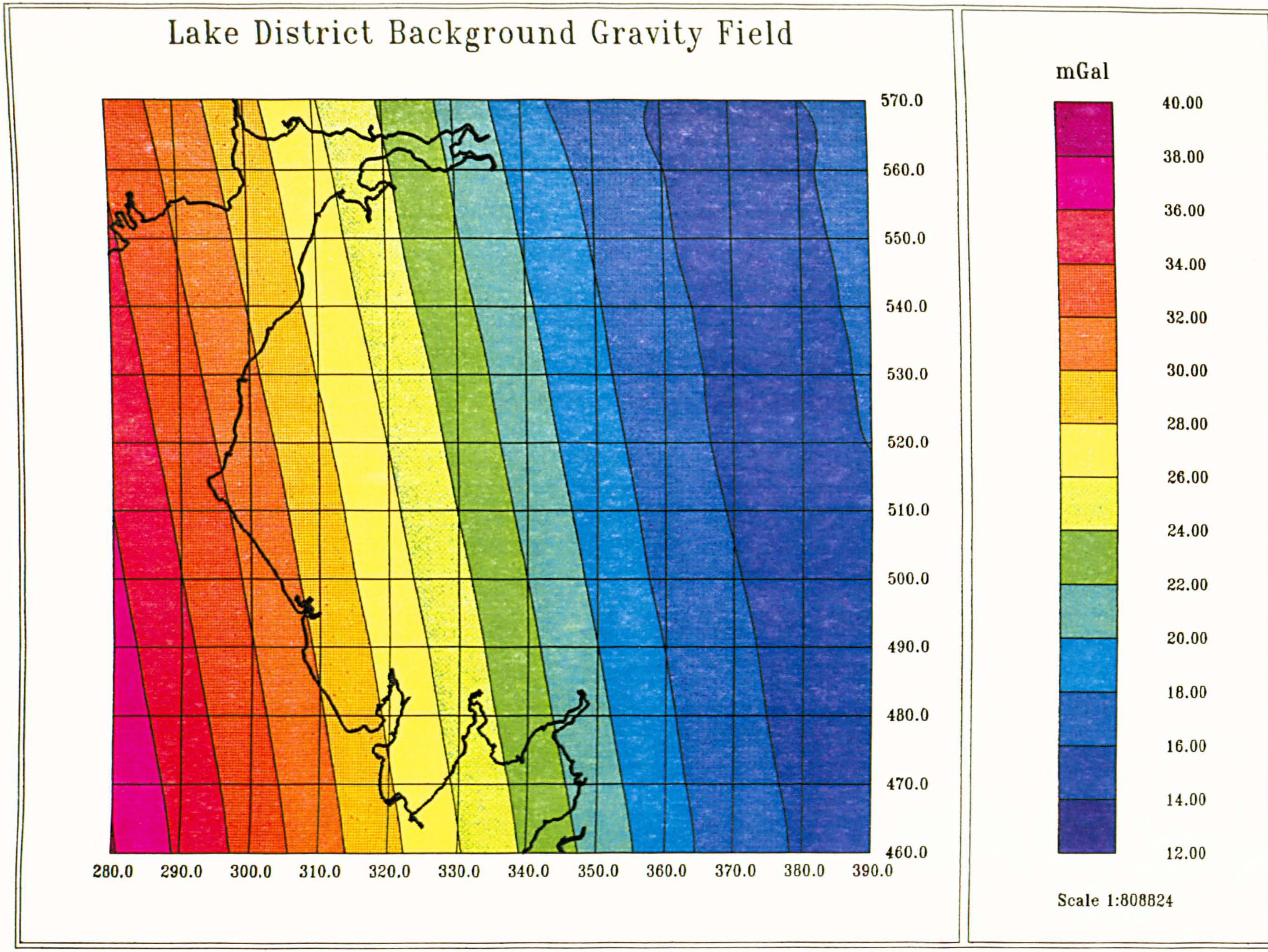


Figure 7.2 Background gravity field adopted for quantitative interpretations.

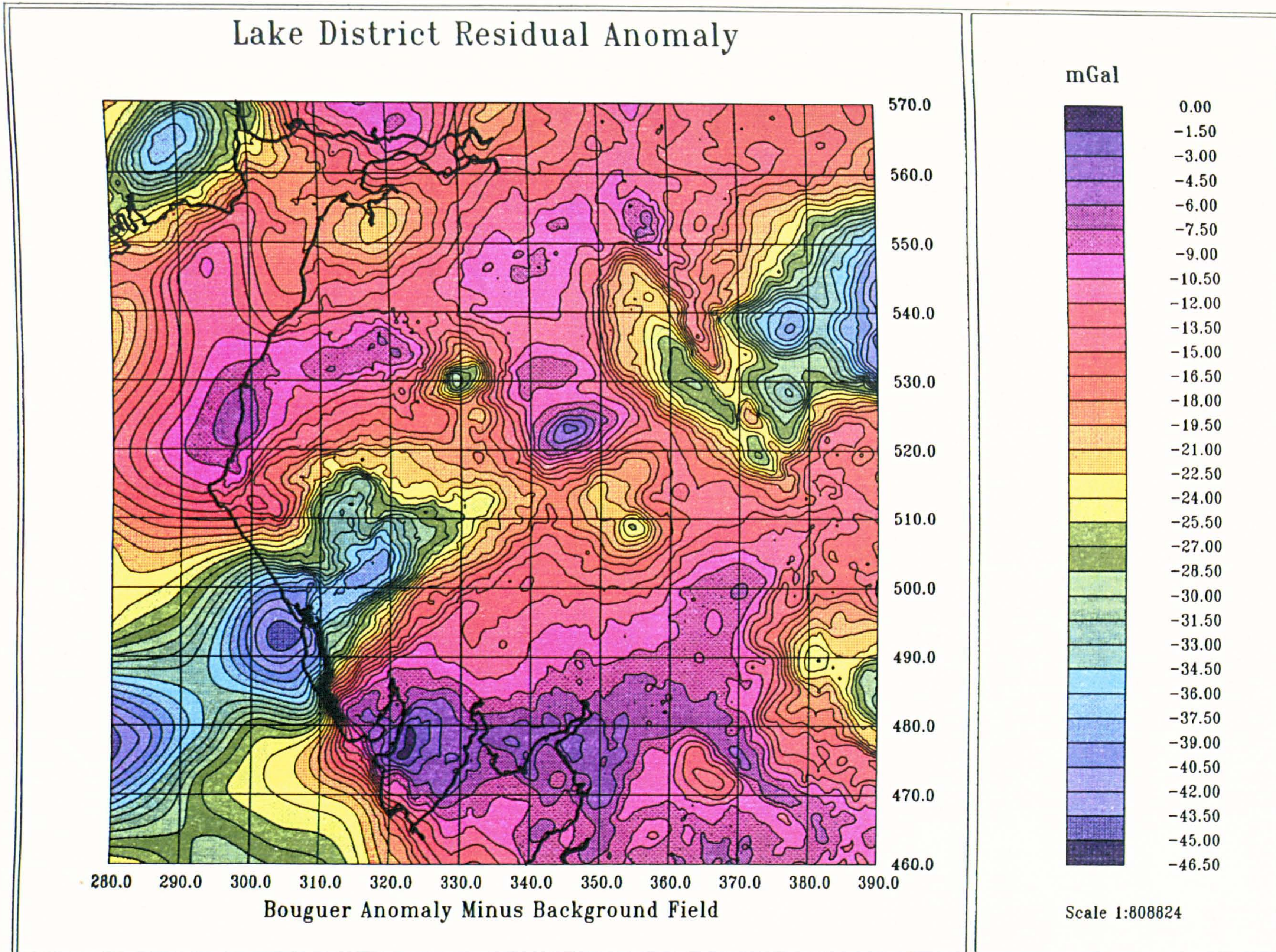


Figure 7.3 Residual gravity field generated by subtracting the background field shown in Figure 7.2 from the observed Bouguer anomaly (the latter calculated using a Bouguer reduction density of 2.78 Mg/m^3).

England between highs over the Irish Sea and North Sea is probably related to a slight thinning of the crust in the off-shore areas (and possibly a slightly denser lower crust?).

The problems associated with estimating the background magnetic field are somewhat different. The magnetic field in northern England is dominated by long wavelength (i.e. deep-seated) anomalies (see Figure 6.19) and the value of the field in the absence of these is difficult to define. A procedure similar to that used to estimate the background gravity field was adopted. An attempt was made firstly to model the anomalies against a background of zero but it became clear that a background field of at least -30 nT would be required. A value of -50 nT was eventually adopted as the most appropriate value for the area as a whole.

7.3 PHYSICAL PROPERTIES AND INITIAL ASSUMPTIONS

Physical property values used in the interpretations are given in Table 7.1. Density and suceptibility values for formations exposed at the surface are based on those discussed in Chapter 5 unless stated otherwise. Properties for concealed formations and buried components of the batholith are inferred from the range of values for similar rocks at outcrop and/or the constraints inferred from the modelling process.

The most important initial assumption related to interpretation of the gravity data concerns the nature of the concealed batholith. As explained in Section 5.4, grain density values for the Eskdale Granite, Eskdale Granodiorite and Ennerdale Granophyre offer no convincing evidence for systematic (gradual) density variations across these intrusions. This is particularly important in the western part of the

Lake District, where Bott (1974 and 1978) assumed a zoned batholith with density values increasing from 2.61 Mg/m^3 in Eskdale to 2.68 Mg/m^3 on the northern margin. Density values presumably must increase towards the margins of the batholith to explain the shape of the gravity anomaly (Bott 1974 & 1978). However, the variation may be in the form of a series of major intrusions (batholith components) rather than a fine zonation; indeed, Bott adopted such a solution for the central (concealed) part of the batholith.

Preliminary modelling for the present study, suggested that the concept of discrete batholith components was both feasible and compatible with the image processing results and geological information. The models shown below were, therefore, developed around this concept, the extent and form of each component being refined during the course of the modelling. The half-widths of the components were estimated initially from the gravity and aeromagnetic maps and the values refined during the modelling using information from adjacent and/or intersecting profiles. The assumption of discrete components, each characterized by a particular bulk density value, does not preclude the possibility that an element of fine zonation may exist, especially within the concealed components.

Magnetic anomalies fall into two categories, namely those related to near-surface magnetic rocks, such as the Eycott lavas, and longer wavelength anomalies related to the deeper basement (see discussion in Section 6.8). The latter are particularly difficult to interpret because there are no obvious correlatives at outcrop and a whole range of models can be made to fit the observed anomalies. After much preliminary modelling it was decided to adopt a susceptibility of

0.02 SI for concealed magnetic basement. This value is consistent with the possibility that the concealed basement comprises magnetic early Ordovician (Arenig) siltstones, mudstones and greywacke-sandstones similar to those found in the Beckermonds Scar borehole. The susceptibility of the Beckermonds Scar rocks is around 0.03 SI (Wilson and Cornwell 1982) but if it is assumed that a some of this is due to contact metamorphism adjacent to the Wensleydale Granite (see discussion in Section 6.8) a lower value of 0.02 SI would seem appropriate for concealed strata away from the granite. In addition, such a value would not be inconsistent with a possible alternative hypothesis that the long wavelength magnetic anomalies represent moderately magnetic concealed crystalline basement.

The reasoning behind specific assumptions and possible alternatives, related to both the batholith and other structures, are discussed in detail in the appropriate sections below.

Table 7.1 Property values adopted for 2.5D interpretations

FORMATION (code)		DENSITY Mg/m^3 (1)	HALF-WIDTH km (2)	MAGNETIC SUSCEPT. SI (1)
Permo-Triassic				
Stanwix Shales (SS)		2.50		
St Bees & Kirklinton Sandstone (SSB)		2.42		
St Bees/Eden Shales (SBS/ES)		2.66		
Penrith Sandstone (PS)		2.46		
Average Permo-Trias beneath Stanwix Shales (PT)		2.45		
Carboniferous/Devonian				
Westphalian/Namurian (CW/CN)		2.50		
Mell Fell Conglomerate (MFC)		2.60*		
Dinantian - U. Liddesdale to M. Border gps (DU)		2.66		
Dinantian - Lower Border Group (DL)		2.70		
Silurian				
Kirby Moor Formation (KMF)		2.69		
Bannisdale Slate Formation (BSF)		2.72		
Coniston Grit Formation (CGF)		2.69		
Wenlock to Ashgill strata (WA)		2.74		
Silurian - Lake District undifferentiated (SL)		2.72		
Silurian - Southern Uplands (SU)		2.73 (3)		
Borrowdale Volcanic Group				
Composite formation G	- See Figs. 1.3 and 1.7 for identification of formations	2.75		
.. K		2.72		
.. N+W		2.77		
.. P		2.77		
.. SFT		2.74		
.. DF		2.72		
.. UL		2.76		
.. B		2.73		
.. AIR		2.70		
.. U		2.81		
.. LB5		2.78		
.. LB4		2.78		
.. LB3		2.81		
.. LB2		2.75		
.. LB1		2.76		
Altered lavas around Shap Granite (BS)		2.83		0.02 (4)
Buried magnetic rocks on profile KL (LB)		2.78		0.01 (5)
Eycott and Skiddaw Groups				
Eycott Volcanic Group (EL)		2.74*(6)		(6)
Skiddaw Group undivided (SK)		2.78		
Skiddaw Group - silt/mudstone lithologies (SKM)		2.81		

Table 7.1 continued

FORMATION (code)	DENSITY Mg/m³ (1)	HALF-WIDTH km (2)	MAGNETIC SUSCEPT. SI (1)
<u>Exposed Lake District Granites</u>			
Eskdale Granite (ESG) + Wasdale Granite (WSG)	2.63	15 (7)	
Eskdale Granodiorite (EGD)	2.70	5 (8)	
Ennerdale Granophyre (ENG)	2.62	5	0.005 (9)
Ennerdale Microdiorite (EM)	2.74	2	0.009
Skiddaw Granite - main (SKG)	2.63	7	
Skiddaw Granite - top (SKGT)	2.59	4	
Threlkeld Microgranite (TMG)	2.67	3	
Shap Granite (SHG)	2.66	7	0.0085
<u>Postulated concealed components of the Batholith</u>			
Crummock Granite (CWG)	2.62*	10	
Haweswater Granite (HWG)	2.66*	7 (10)	
Coniston Granite (CNG) - as high level intrusion	2.62*	5	
Coniston Granite (CNG) - as deep-seated intrusion	2.66*	5	
Loweswater Granodiorite (LGD)	2.70*	15 (11)	
Dunmail Granite (DMG)	2.66*	15 (12)	
Buttermere Granite (BMG)	2.68*	15 (13)	
Rydal Granite (RDG)	2.68*	15 (14)	
Ulpha Granite (ULG)	2.65*	7	
<u>Other Granites</u>			
Wensleydale Granite (WNG)	2.62 (15)	10	
Weardale Granite (WEG)	2.63 (16)	10 (17)	
Criffel Porphyritic Granodiorite (CRG)	2.64 (18)	10	0.001 (18)
Criffel Main Granodiorite (CMG)	2.70 (18)	10	0.008 (18)
<u>Concealed Basement</u>			
Undifferentiated basement (UB)	2.78		
Carlisle mafic intrusion (CBI)	2.95*(19)	8	0.03
Magnetic L. Palaeozoic - Askrigg Block (CMA)	2.78		0.03 (20)
Concealed magnetic basement (CMB) & sheets (CMS)	2.78*		0.02 (21)

NOTES

1. The density and susceptibility values used in the modelling were based on the determinations described in Chapters 3 and 5 unless indicated otherwise by the following notes. Density values marked with an asterisk were inferred from the range of values for similar rocks at outcrop and/or constraints inferred from the modelling. Induced magnetization values were calculated by the modelling program (Gravmag) from the susceptibility values listed above assuming the Earth's magnetic field = 38.197 A/m, Declination = -10° and Inclination = 69°.

2. Half-widths were estimated initially from the gravity and aeromagnetic maps and the values refined during the modelling using information from adjacent and/or intersecting profiles.

3. Density of the Silurian sequence in the Southern Uplands from Bott & Mason Smith (1960).

Table 7.1 continued

4. Susceptibility of thermally metamorphosed BVG around the Shap Granite from Locke & Brown (1978) - value based on that for lavas around 20 m from the granite contact.

5. Estimated values for slightly magnetic Lower Borrowdale lavas.

6. Eycott Group lavas have a stong remanent magnetization. Total magnetization vectors have been calculated for each profile from values published by Morris (1973) and Briden & Morris (1973). For profiles AB and CD magnetization = 1.2 A/m, inclination = 46.6^{o}, declination = -2.8^{o}. For profile EF magnetization = 0.25 A/m, inclination and declination as for profiles AB and CD. For profile GH magnetization = 1.0, inclination = 23.4^{o}, declination = 13.7^{o}. Density of Eycott Group lavas estimated from the modelling (see text).

7. Half-width of ESG = 8 km on profile IJ.

8. Half-width of EGD = 15 km in models which show the granodiorite as a marginal phase extending to depth.

9. Susceptibility value represents the combined effects of granophyre and microdiorite.

10. Half-width of HWG = 5 km on profile IJ.

11. Half-width of NCG = 10 km on profiles EF and YZ.

12. Half-width of DMG = 7 km on profile IJ, dens = 2.65 Mg/m^3 on CD.

13. Half-width of BMG = 10 km on profile EF.

14. Half-width of RDG = 6 km on profile IJ and 10 km on profile EF.

15. Wilson & Cornwell (1982) reported a saturated density value of 2.59 Mg/m^3 from the top of the Wensleydale Granite. This value seems unreasonably low when compared with other granites in northern England and may not by typical of the granite at depth. A value of 2.62 Mg/m^3 was, therefore, adopted for the bulk, in-situ density of the Wensleydale Granite.

16. Density of Weardale Granite from Bott (1967).

17. Half-width of western cupola of Weardale granite = 7 km.

18. Density and susceptibility values for the Criffel Granodiorite from Bott & Mason Smith (1960).

19. Density value for the Carlisle intrusion based on gabbro. Susceptibility value assumes a moderately magnetic intrusion.

20. Magnetic susceptibility of Lower Palaeozoic rocks around the Wensleydale Granite from the Beckermonds Scar borehole (Wilson & Cornwell 1982).

21. Susceptibility of concealed magnetic basement based on values from the Beckermonds Scar borehole (see text).

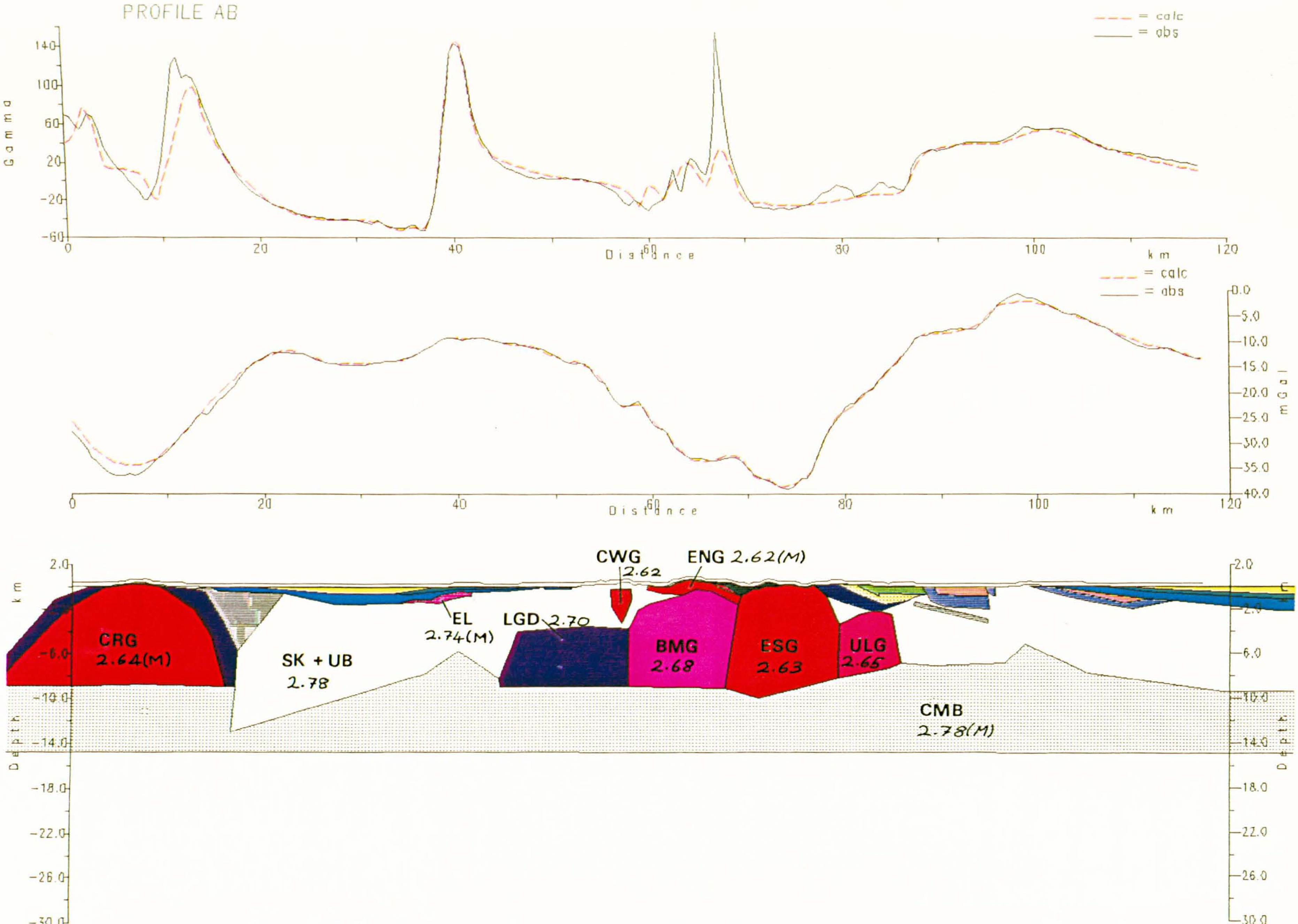


Figure 7.4 Interpretation along profile AB.

7.4 PROFILE AB

Profile AB runs southwards from the Criffel Granodiorite, in the Southern Uplands, across the western Lake District where the Ennerdale Granophyre and Eskdale Granite are exposed at outcrop. The final interpretation is shown in Figure 7.4 with details of the northern, central and southern parts of the profile shown in separate figures below. Figure 7.5 (central section) also illustrates the contributions of individual parts of the model. A fold-out key to these and other models in Chapter 7 is provided at the end of the chapter.

7.4.1 The batholith

The negative gravity anomaly over the Lake District batholith is explained in terms of four major batholith components and two smaller, high-level granitic intrusions (Figure 7.5). The Eskdale Granite (ESG) forms the central, lowest density component. The gravity anomaly over the outcrop can be explained entirely in terms of the measured surface density contrast between the Eskdale Granite (2.63 Mg/m^3) and the Skiddaw Group (2.78 Mg/m^3) extending to a depth of around 9 km. There would seem to be, therefore, no positive geophysical evidence to suggest that the outcrop is underlain by a later intrusion, as has been proposed on geochemical grounds (O'Brien et al. 1985). However, it should be noted that the preferred interpretation does not preclude the possibility of a separate underlying intrusion of the same density as the Eskdale Granite, or even a slightly lower density.

The Ennerdale Granophyre (ENG) is of slightly lower density than the Eskdale Granite (Table 7.1) yet its associated gravity anomaly is less negative. This implies that the intrusion is either significantly

Extended caption for Figure 7.5 (following page)

The figure shows the central part of profile AB. The observed gravity and magnetic fields (thin black lines) and calculated fields (dashed red lines) are as in Figure 7.4. The thick dashed lines indicate the calculated fields with parts of the model removed (i.e. set to background values) as follows: A = calculated gravity anomaly in the absence of the Borrowdale Volcanic Group (bodies LB3, LB4, AIR, UL); B = as for A but further in the absence of the Ennerdale Granophyre (ENG), Ennerdale Microdiorite (EM) and Crummock Granite (CWG); C = as for B but further in the absence of the Loweswater Granodiorite (LGD) and Ulpha Granite (ULG); D = as for C but further in the absence of the Buttermere Granite (BMG); E = calculated magnetic anomaly in the absence of the Ennerdale Granophyre (ENG) and the Ennerdale Microdiorite (EM).

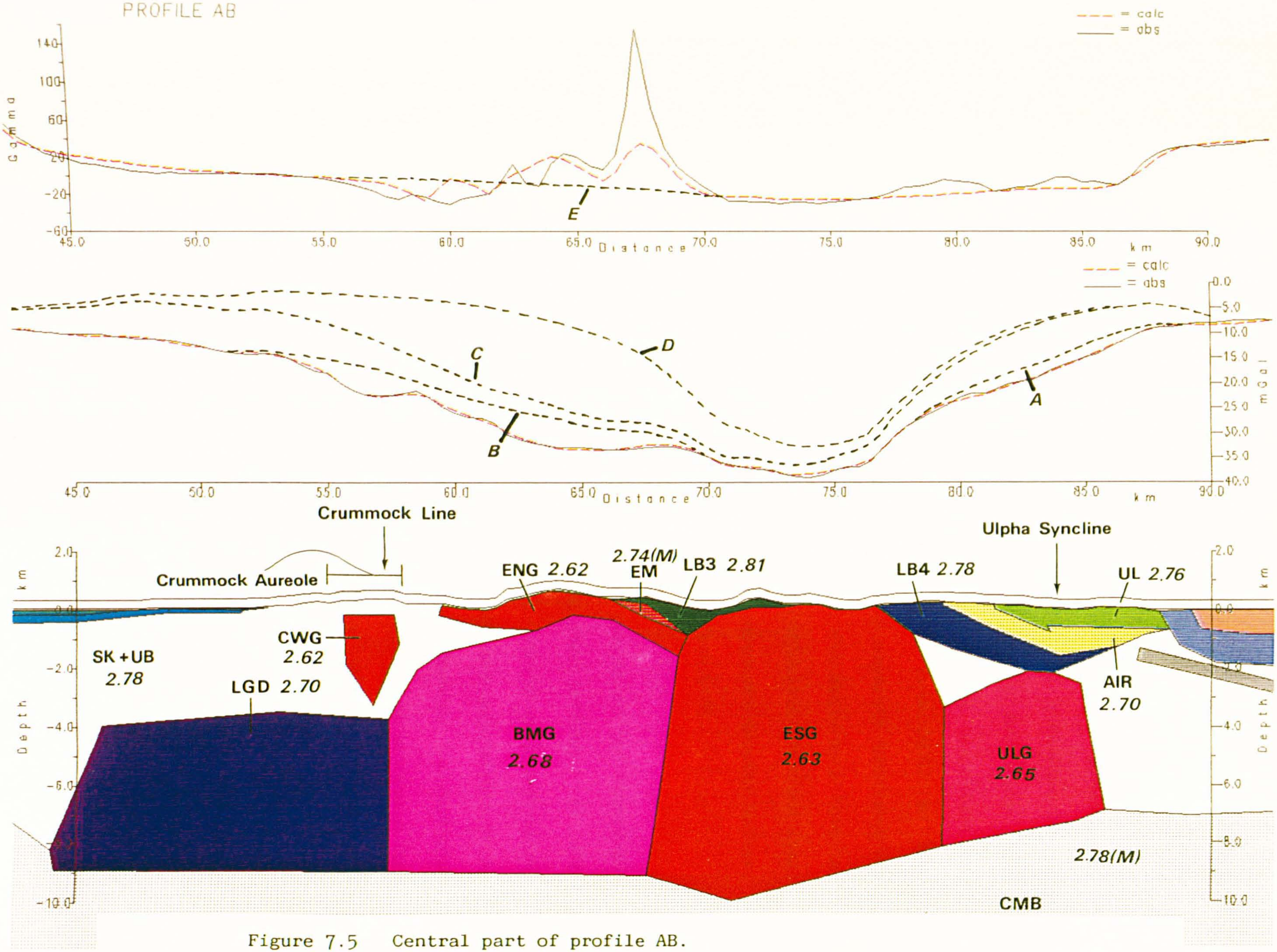


Figure 7.5 Central part of profile AB.

thinner than the Eskdale Granite or that it is underlain by a separate intrusion of higher density. The preferred interpretation follows Bott (1974) in assuming that the latter is more feasible but unlike his model, no density zonation within the underlying intrusion is assumed. A good fit to the gravity anomaly across this part of the profile is achieved with the granophyre of thickness 1 to 2 km, underlain by an intrusion of mean density 2.68 Mg/m^3. The concealed intrusion lies between the Eskdale Granite and the Crummock lineament (lineament 1, Figure 6.17) and probably extends to around the same depth as the Eskdale Granite. It appears to be an identifiably separate component of the batholith and is henceforth referred to as the Buttermere Granite (BMG). A density value of 2.68 Mg/m^3 implies a composition between that of granite and granodiorite, when compared with measured density values for Lake District granitoids at outcrop (see Section 5.4).

Variations on the preferred model in the region of the Ennerdale Granophyre are possible because changes in the thickness of the granophyre can be offset against changes in the density or thickness of the underlying intrusion. However, the form of the granophyre as a relatively thin body is more clearly constrained towards its northern margin (x = 60 km on profile AB). Here it is difficult to achieve a fit to the gravity data without placing the base of the granophyre well above the top of the underlying intrusion (Figure 7.5), always assuming, of course, that there is no lateral density variation within the concealed body. The model also shows the granophyre extending southwards beneath a thin cover of Borrowdale Volcanic rocks adjacent to where it is observed at outcrop a couple of kilometres to the west of profile AB (see Figure 7.1 for the position of the lines in relation to the outcrop).

The magnetic field over the Ennerdale Granophyre is not sufficiently well defined by the regional aeromagnetic data to enable detailed modelling to be carried out. The granophyre itself has a very low magnetic susceptibility and the anomalies are presumed to be due to sheets of magnetic microdiorite which are common within the intrusion (see Sections 1.2.4, 5.4.3 and Chapter 6). For the purpose of the present interpretation a uniform susceptibility of 0.005 SI was adopted for the granophyre to represent the combined effects of both rock types. The resulting model gives a surprisingly good fit to the aeromagnetic field and tends to confirm that the source of the observed magnetic anomalies lies within the Ennerdale Granophyre rather than beneath it. A large area of hybrid rock/microdiorite has been mapped in the southern part of the main outcrop of the Ennerdale Granophyre just to the west of profile AB between x = 65 and X = 67 km (Figure 1.3). This is included as a separate body in the model (EM, Figure 7.5 and Table 7.1) in the form of a thin sheet on the top surface of the granophyre. Its calculated magnetic anomaly coincides with the main peak in the observed magnetic field (at x = 68 km), suggesting that a microdiorite sheet is indeed the causative body, although the calculated amplitude is lower.

Profile AB crosses the Crummock aureole (see Sections 1.2.1 and 6.7) between x = 55 and x = 58 km (Figure 7.5). A change of gradient on the Bouguer anomaly map in this area was first noted by Bott (1974). His two-dimensional interpretation showed an underlying 'granite' ridge which was assumed to be the northernmost component of the Lake District batholith. The gravity anomaly is more clearly defined by the present data as a small secondary low on the northern flank of the main negative anomaly over the batholith. Density measurments were made on samples of Skiddaw Group mudstones from outside and within the aureole, and along a traverse across the contact, to establish whether the altered Skiddaw Group rocks themselves might be the cause of the anomaly. The results are given in Section 5.6 (Figure 5.22 and Table 5.8). These show that grain densities are about 0.2 Mg/m^3 lower within the bleached zone but porosity values are also lower by 1 to 2 % which results in the mean saturated density being about 0.01 Mg/m^3 higher. Variation is greater within the bleach zone but in terms of bulk (in-situ) density there is little change across the contact, and the effect of the chemical changes and recrystallisation within the Skiddaw Group mudstones can be discounted as the primary cause of the gravity anomaly on profile AB (see, however, interpretations along other profiles below).

Some modelling was carried out by the author during an earlier phase of the present project as part of a multidisciplinary study of the Crummock aureole (Cooper et al. 1988, included as supplementary paper S2 in Appendix 2). The interpretation has been refined by the present work and modified in some respects, but the principal conclusions are still valid. The relatively small amplitude of the gravity anomaly precludes the presence of a large granite pluton and the anomaly is best explained in terms of a high level intrusion emplaced close to the northern margin of the Buttermere Granite, along the Crummock lineament. Three alternative interpretations were considered feasible by Cooper et al. (see Figure 7.6, which shows models for a profile approximately 2 km east of AB). These explained the anomaly in terms of either a high level granitic laccolith (Figure 7.6c), a ridge on the northern margin of the Buttermere Granite

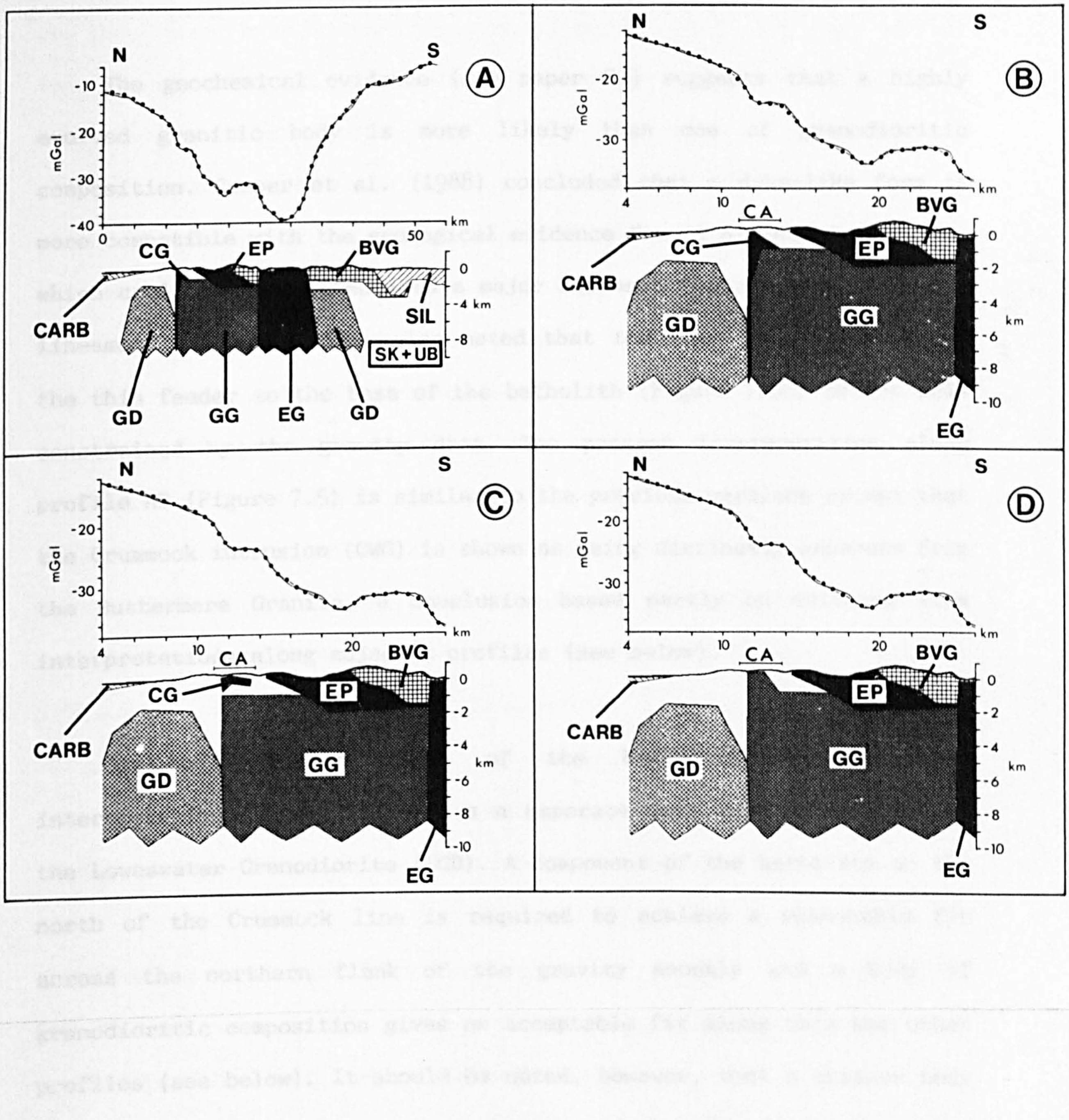


Figure 7.6 Gravity interpretation across the Crummock aureole from Cooper et al. (1988) - their section 1 (B shows details of model A in the region of the Crummock Aureole, C and D show alternative models for the Crummock anomaly). The codes shown on this figure differ from those used elsewhere in this work - they are translated as follows: BVG = Borrowdale Volcanic Group undivided, CA = Crummock Aureole, Carb = Carboniferous undivided, CG = Crummock Granite (CWG), EG = Eskdale Granite (ESG), EP = Ennerdale Granophyre (ENG), GD = Loweswater Granodiorite (LGD), GG = Buttermere Granite (BMG), SIL = Silurian undivided, SK = Skiddaw Group, UB = basement undivided.

(Figure 7.6d) or a high level granitic body with a dyke-like form along the northern side of the Buttermere Granite (Figure 7.6 a & b).

The geochemical evidence (see paper S2) suggests that a highly evolved granitic body is more likely than one of granodioritic composition. Cooper et al. (1988) concluded that a dyke-like form is more compatible with the geological evidence for an elongated intrusion which could be associated with a major basement fracture (the Crummock lineament). However, they also noted that the form (or existence) of the thin feeder to the base of the batholith (Figure 7.6b) is not well constrained by the gravity data. The present interpretation along profile AB (Figure 7.5) is similar to the previous versions except that the Crummock intrusion (CWG) is shown as being distinctly separate from the Buttermere Granite, a conclusion based partly on evidence from interpretations along adjacent profiles (see below).

On the northern flank of the batholith the preferred interpretation (Figure 7.5) shows a separate component referred to as the Loweswater Granodiorite (LGD). A component of the batholith to the north of the Crummock line is required to achieve a reasonable fit across the northern flank of the gravity anomaly and a body of granodioritic composition gives an acceptable fit along this and other profiles (see below). It should be noted, however, that a thinner body of lower density could account equally well for the observed gravity data.

On the southern flank of the batholith a number of interpretations is possible. Bott (1974 & 1978) demonstrated that granite must underlie the Borrowdale Volcanic sequence and his interpretation showed a concealed granite shelf as a southward continuation of the Eskdale Granite. The new gravity data define the shape of the gravity anomaly in this area more accurately and, together with the new density measurements (Chapter 5), enable the effect of the Borrowdale Volcanic rocks to be taken into account. Profile AB shows a steep gravity gradient over the southern flank of the Eskdale Granite and then a slight flattening to the south over the Borrowdale Volcanic sequence between approximately x = 80 km and x = 87 km. This flattening of the anomaly is centred around the Ulpha Syncline (at x = 83.5 km, Figure 7.5) and begs the question as to whether the effect is due to an underlying component of the batholith or a thickened volcanic sequence. In the case of the former, the most obvious alternatives would appear to be a southerly extension of the Eskdale Granite, as implied by Bott's (1974 and 1978) model, or an easterly (concealed) extension of the Eskdale Granodiorite, which crops out about 5 km to the west of profile AB. However, a third alternative, in terms of a separate concealed intrusion beneath the Ulpha Syncline (the Ulpha Granite, ULG), is considered equally feasible and has some support from interpretations along adjacent profiles (e.g. KL, SEction 7.7).

The two 'end-member' interpretations are shown in Figures 7.5 and 7.7. In the case of the former, the Borrowdale Volcanic sequence is assumed to thin rapidly along the southern margin of the Lake District, with no great thickening over the Ulpha Syncline. The alternative interpretation (Figure 7.7) also gives a good fit to the gravity field but requires that the entire Upper Borrowdale Volcanic sequence is of a density similar to that of the Airy's Bridge Formation and must thicken considerably beneath the syncline. Even in these circumstances, a southerly extension of the Eskdale Granite at depth is still necessary.

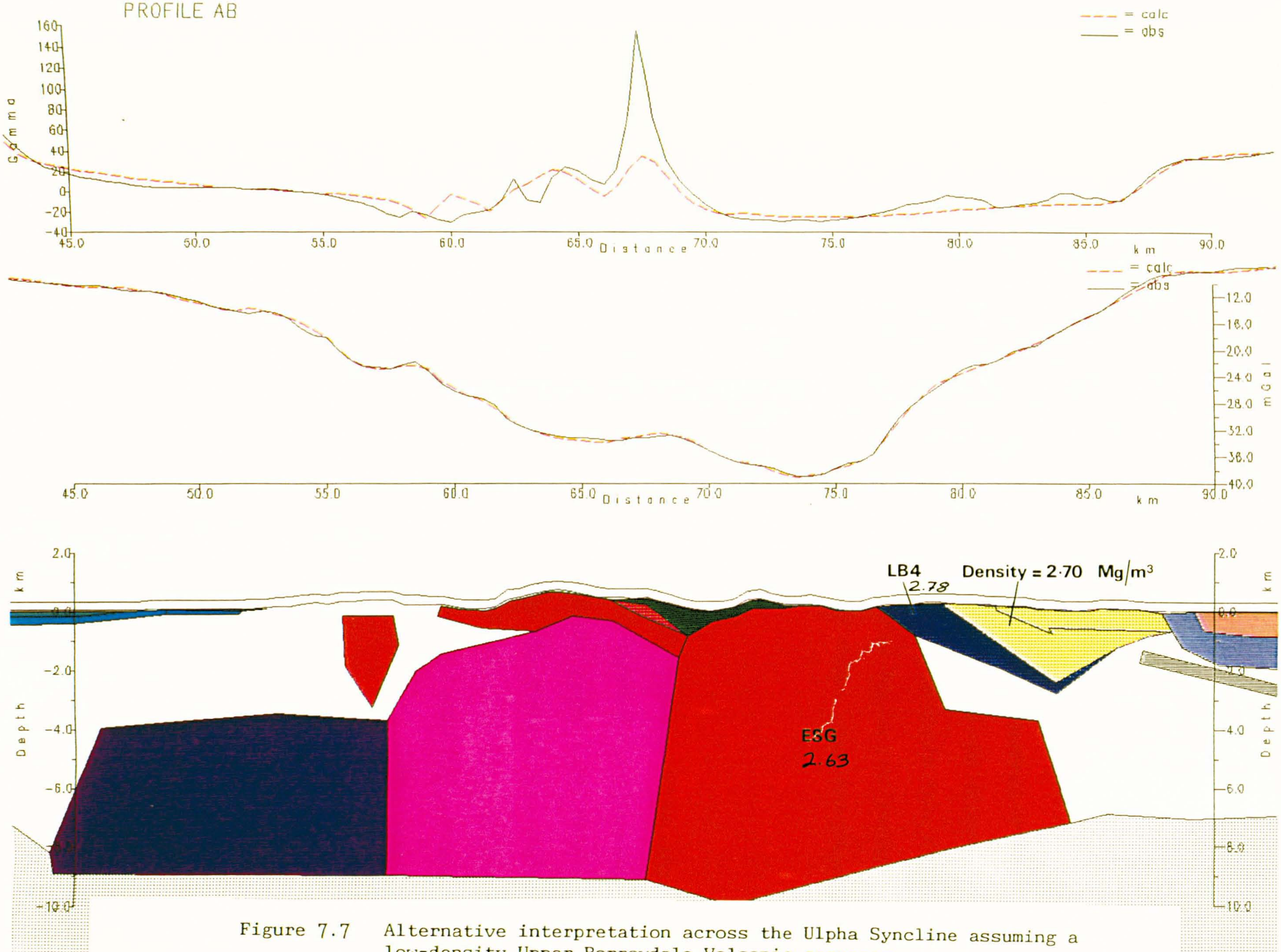


Figure 7.7 Alternative interpretation across the Ulpha Syncline assuming a low-density Upper Borrowdale Volcanic sequence.

Recent geological mapping (D. Millward and E.W. Johnson, pers. comm.) indicates that there is some thickening of the upper BVG within the Ulpha Syncline and the Airy's Bridge Formation may be around 1.2 to 1.4 km thick (i.e. thicker than that shown in Figure 7.5). However, it seems unlikely that the sequence could be sufficiently thick, or overall of sufficiently low density, to explain the anomaly entirely without recourse to an underlying (possibly separate) component of the batholith. The truth possibly lies somewhere between the two extremes, but at the present state of knowledge the balance of evidence from this and other profiles tends towards the model shown in Figure 7.5 (perhaps with a slightly thicker Airy's Bridge Formation) rather than that shown in Figure 7.7.

7.4.2 Northern part of profile AB

Profile AB crosses the prominent magnetic anomaly along the northern margin of the Lake District (anomaly EY Figure 6.17) at around $x = 40$ km. The anomaly is related to Eycott Group lavas which have a strong remanent magnetization where they crop out farther east (the reader is referred to the discussion of profile CD (Section 7.9) for details of their physical properties). Preliminary modelling of the Eycott anomaly along profile AB demonstrated that a simple model involving near-surface magnetic lavas alone could not give a satisfactory fit to the magnetic field. The problem is illustrated by examining the shape of the anomaly. To the south of the main maximum the residual field flattens off to a value of around 0 nT whereas to the north it flattens off to around -40 nT, with no pronounced negative anomaly immediately to the north of the maximum (Figure 7.4). It became clear that the observed field could only be modelled satisfactorily in terms of the combined effects of the Eycott lavas and a deeper magnetic basement responsible for the long wavelength components of the field. The form of this magnetic basement is discussed in more detail in Section 7.4.3.

The eventual model for the Eycott lavas (Figure 7.8) shows a layer about 0.6 km thick extending northwards from x = 41.5 km at shallow depth (around 0.6 km) beneath the Carboniferous cover and thinning northwards beneath the Solway Basin. The Lower Carboniferous sequence is shown as directly overlying the Eycott Group but an equally good fit can be obtained with a slightly thinner Carboniferous sequence between x = 34 and x = 38 km underlain by Silurian rocks as indicated for profile CD (see Section 7.9, Figure 7.31). In either case the model is compatible with the concept of a relatively simple (layered) structure for the concealed Lower Palaeozoic rocks beneath the northern margin of the Lake District and the subsequent development of the Solway Basin along growth faults (along its present southern margin) during the Lower Carboniferous. However, an equally good fit to the Eycott magnetic anomaly can be achieved with the lavas dipping more steeply to the north (Figure 7.9). In this model a layer of preserved Silurian strata is shown beneath the Carboniferous between x = 35 and x = 38 km but, as with the previous example, this could be traded off against a slightly thicker Carboniferous sequence. The important point to note regarding this interpretation is that high density 'basement' (SK+UB, Skiddaw Group ?) lies above the Eycott Group from about x = 37 km northwards which in turn implies that the northern margin of the Lake District was affected by significant, southwards directed, post-Llanvirn (Acadian ?) thrusting.

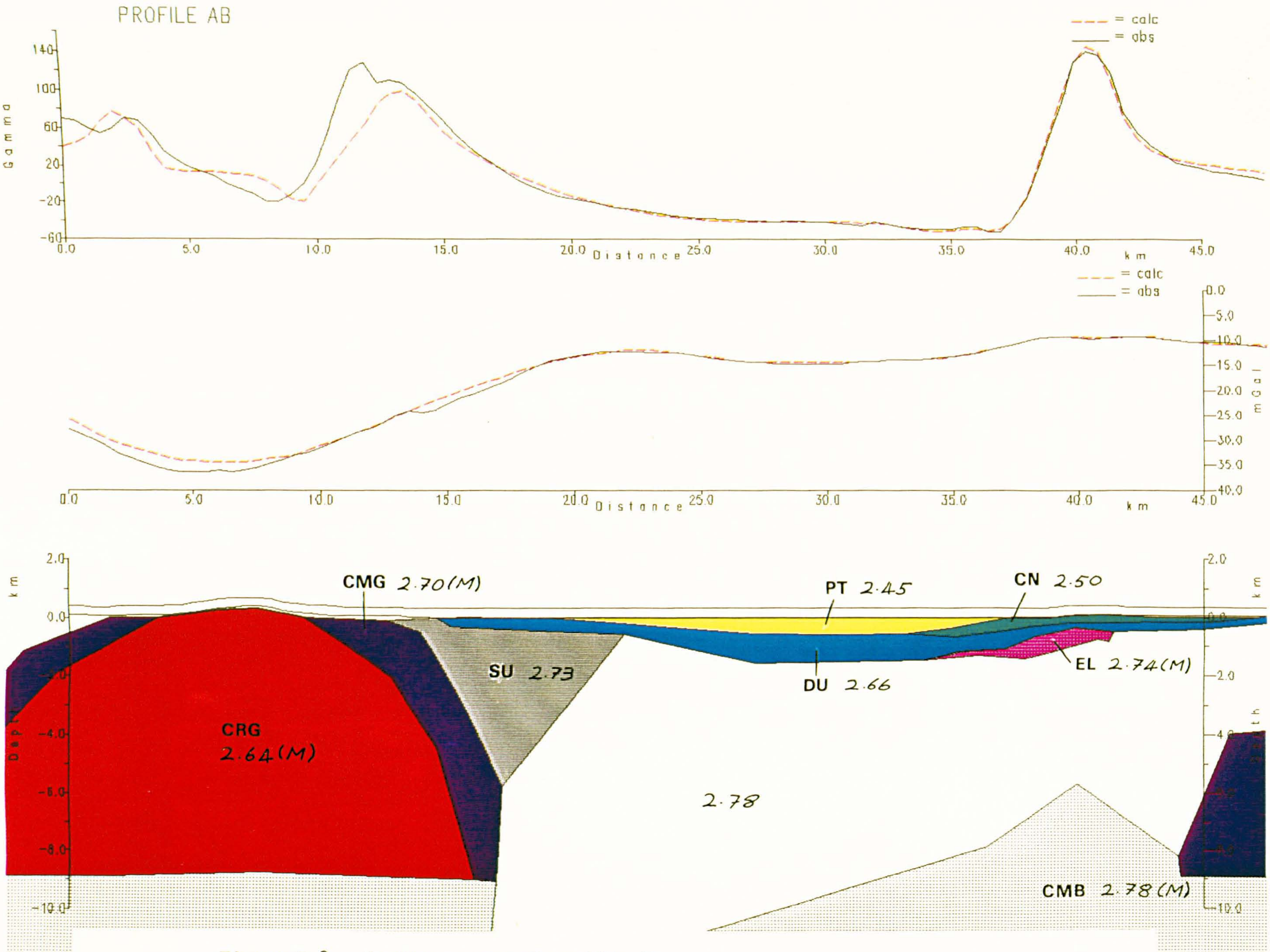
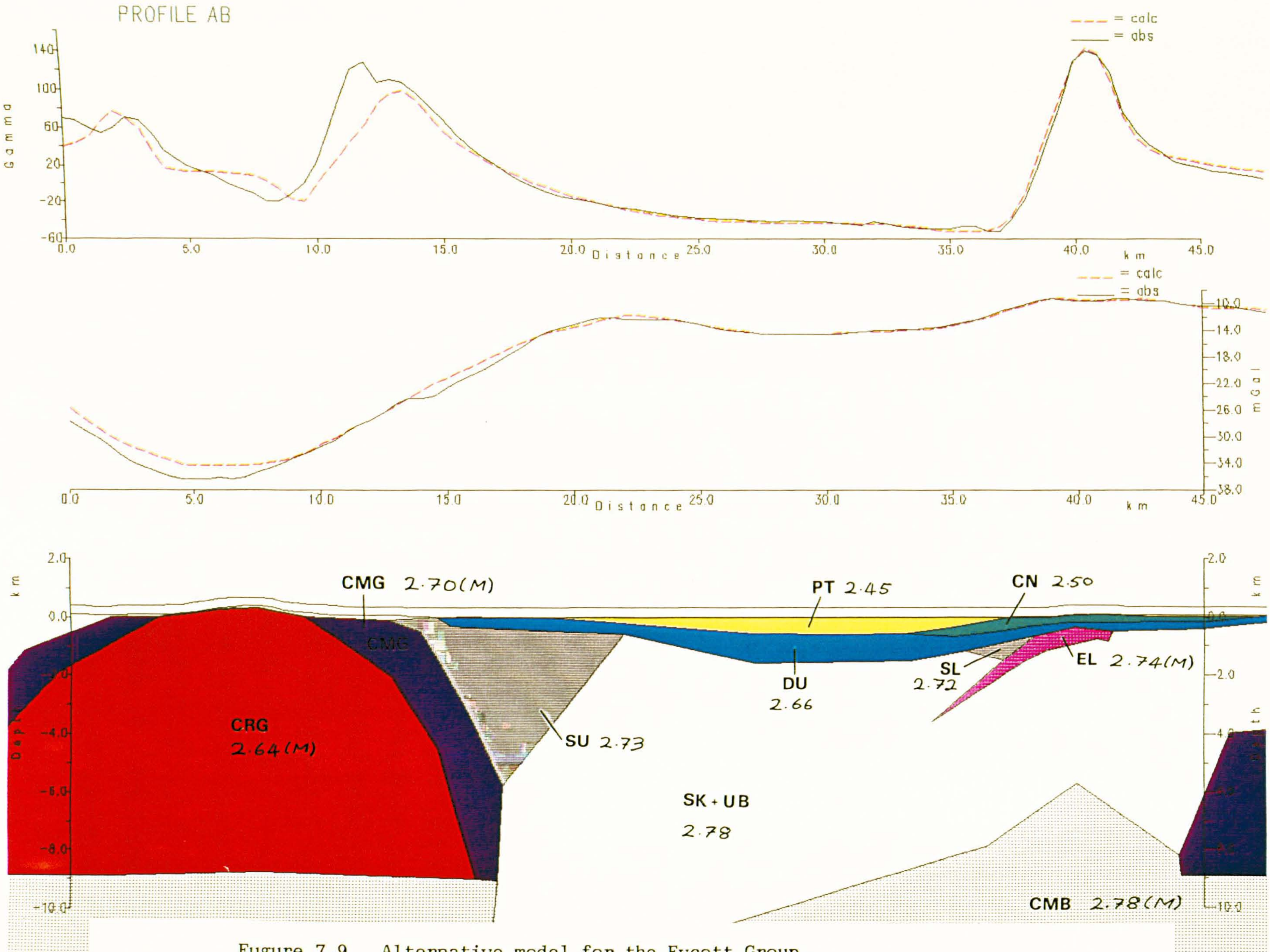


Figure 7.8   Northern part of profile AB.



Fugure 7.9 Alternative model for the Eycott Group.

Farther north, across the Solway Basin, the negative gravity anomaly can be explained in terms of a Permo-Triassic sequence thickening to approximately 0.5 km at around $x = 30$ km, lying unconformably above a Lower Carboniferous sequence about 1 km thick. The Westphalian and Namurian sequences pinch out towards the centre of the basin as indicated by borehole and seismic evidence farther east (see profile CD, Section 7.9).

Prominent gravity and magnetic anomalies are associated with the Criffel Granodiorite to the north of the Solway Basin. The negative gravity anomaly was interpreted by Bott & Masson Smith (1960) in terms of a zoned intrusion with density increasing towards the margins from 2.64 Mg/m^3 in the central 'porphyritic granodiorite' to 2.71 Mg/m^3 in the outer 'main granodiorite'. For the purpose of the present interpretation a simple two phase model has been adopted. The magnetic anomaly is in the form of an annular high over the margins of the intrusion, with a central low over the porphyritic granodiorite. The author is not aware of any published susceptibility values for either the intrusion itself or the surrounding Silurian rocks. However, a reasonably good fit to both the magnetic and gravity anomalies is achieved if the denser margins of the intrusion are assumed to be moderately magnetic (0.008 SI, cf the Shap Granite and the Ennerdale Microdiorite, Chapter 5) and if the central part is assumed to be slightly magnetic (0.001 SI, i.e. a value between that adopted for the marginal granodiorite and the measured value for the Eskdale Granite). The model demonstrates that the source of the magnetic anomaly lies within the intrusion but no attempt has been made to refine the interpretation as the Criffel Granodiorite is marginal to the main area of interest in the Lake District.

The main point to note about the model is that the Silurian sequence on the southern side of the granodiorite thins rapidly southwards towards the Solway Basin. Beneath the central part of the Solway Basin the model shows the Lower Carboniferous sequence resting directly on 'basement' of density 2.78 Mg/m^3 which could represent Skiddaw Group rocks (or their equivalent) or undefined basement of similar density. Silurian rocks in the Lake District and Southern Uplands are less dense than the Skiddaw Group, at around 2.72 - 2.73 Mg/m^3 (Chapter 5 and Table 7.1). The presence of a thin layer of Silurian rocks beneath the Solway Basin could be accommodated if the Permo-Triassic and Carboniferous sequences were thinner than shown on the model. However, if the background field has been correctly defined, the interpretation gives little scope for any great thickness of Silurian strata.

7.4.3 Magnetic basement and the southern part of profile AB

Initial attempts to model the long wavelength magnetic anomalies across the Lake District, on this and other profiles, were based on the assumptions that (a) magnetic rocks concealed beneath the Windermere Group were responsible for the the highs in the southern part of the area (anomalies CM and WI, Figure 6.17), (b) these rocks were cut out to the north by the granitic batholith, and (c) the magnetic field on the northern margin of the Lake District could be modelled solely in terms of the Eycott lavas. It became apparent, however, that assumptions b and c were flawed on a number of counts. Firstly, models in which magnetic basement beneath the Windermere Group terminated south of the batholith produced a magnetic low of unacceptably large amplitude over the granites. An acceptable fit could be produced only by continuing the magnetic rocks northwards beneath the batholith.

Secondly, the difference in the levels of the magnetic field to the north and south of the Eycott anomaly, referred to in the previous section, could only be modelled by assuming that magnetic rocks lie concealed at depth on the northern side of the batholith and then dip northwards beneath the Solway Basin. Although, at first sight, the shape of the magnetic field along the northern margin of the Lake District gives little indication of the presence of magnetic basement at depth, on closer examination it is apparent that the large anomaly over the Eycott lavas obscures a low amplitude positive anomaly which is along strike from the large positive anomaly over the Isle of Man (see Figure 6.19 and discussion of anomalies in Section 6.8).

A whole range of models based on the concept of magnetic basement extending beneath the batholith towards the northern margin of the Lake District is possible. However, the form of the magnetic basement is constrained by the shape of the batholith necessary to fit the gravity anomaly and has to be consistent across all profiles. The final interpretation shown in Figure 7.4 is considered a reasonable compromise given the uncertainties of dealing with unknown and deeply buried rocks. A susceptibility value of 0.02 SI was adopted for the magnetic basement and it is assumed to have no significant density contrast with the overlying non-magnetic rocks (which must be Skiddaw Group or undefined formations of similar density). These values are consistent both with a sequence of early Ordovician (Arenig) rocks, similar to those encountered at Beckermonds Scar, or with moderately magnetic 'crystalline basement'. The model shows the magnetic basement reaching to within about 5 km of the surface beneath the Furness inlier of the Skiddaw Group (at x = 99 km, Figures 7.4 and 7.10) and extending to the mid crust (around 15 km). It should be noted, however, that only a slight alteration of the background magnetic field, and a small reduction in the assumed susceptibility of the basement are required in order to achieve a reasonably good fit to the observed magnetic field with the magnetic basement extending right down to the base of the crust.

Along the southern side of the batholith there is a conflict between the depth extent of the granites necessary to fit the gravity field and the requirement for magnetic basement to extend northwards in order to fit the magnetic anomaly. As in other situations, a variety of models is possible. The solution eventually adopted assumes that the base of the batholith must thin southwards and be immediately underlain by the magnetic basement. In fact, the base of the batholith is shown as being in contact with the top of the magnetic basement over its entire width but this need not necessarily be the case (see models for other profiles below). Beneath the northern margin of the Lake District the magnetic basement again reaches to within about 6 km of the surface before deepening northwards beneath the Solway Basin. Some of the alternative models for the form of the magnetic basement are discussed in relation to the other profiles below.

Low amplitude magnetic anomalies occur over the outcrop of the Borrowdale Volcanic Group between the Eskdale Granite and the Windermere Group (Figures 7.4 and 7.5). These probably relate to magnetic lavas within the volcanic pile (see Chapter 5) but no attempt has been made to model them in detail. However, a sharp step in the magnetic field occurs south of x = 86 km (Figure 7.10) which requires an explanation. The anomaly cannot be explained satisfactorily in terms of a ridge in the magnetic basement and a relatively shallow body is

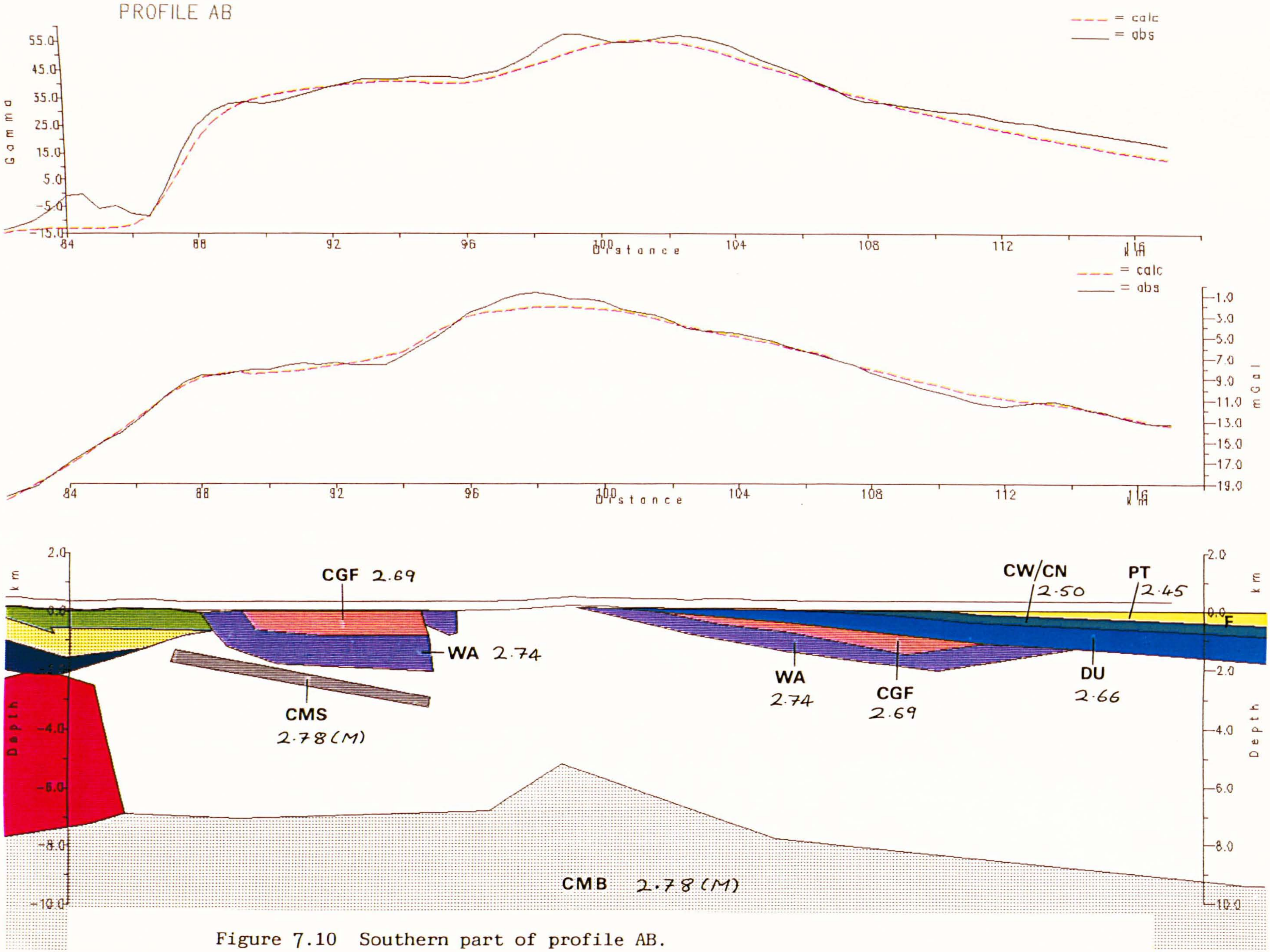


Figure 7.10 Southern part of profile AB.

required. The preferred model shows a thin sheet of magnetic material (CMS), underlying the Windermere Group, with the same susceptibility value as the magnetic basement. Such a body could represent either a layer of magnetic volcanic rocks or possibly a sliver of magnetic basement emplaced at a higher structural level by northwards directed thrusts. The tectonic implications of this, and of the postulated shape of the concealed magnetic basement, are discussed further in Chapter 8.

7.5 PROFILE WX

Profile WX was positioned (see Figure 7.1) with three objectives in mind. These were (1) to examine the relationship between the Ennerdale, Wasdale and Eskdale intrusions, (2) to model the Crummock anomaly in the Crummock Water area, and (3) to investigate the cause of the Coniston gravity low (CN, Figure 6.17). The batholith is assumed to thin southwards as suggested by the interpretation along profile AB but this assumption is not critical to the interpretation of the near-surface structure. The negative anomaly across the batholith is strongly asymmetrical, as on profile AB, and shows distinctive secondary lows over the Ennerdale Granophyre, the Crummock aureole and on the southern flank over the Coniston low (Figure 7.11). The most satisfactory fit to the gravity field was achieved with the same broad-scale form of the batholith as was established for profile AB.

The central part of the profile (between x = 23 and x = 32.5 km) lies within the metamorphic aureole which encompasses the outcrops of the Eskdale and Wasdale granites (Figure 1.3). The Wasdale outcrop is usually considered to be part of the Eskdale Granite, or closely related to it (see Section 1.2.4) and density measurements from both outcrops show no appreciable difference (see Section 5.4). Two alternative interpretations are shown (Figures 7.11 and 7.12), both of which appear to support the contention that the Eskdale and Wasdale granites are part of a single intrusion and both show granite lying at very shallow depth beneath the Borrowdale volcanics to the south of the Wasdale outcrop.

The gravity gradient is very steep immediately to the north of the Wasdale outcrop. In Figure 7.11 this is interpreted in terms of an almost vertical northern margin to the Eskdale/Wasdale intrusion. The gradient corresponds to (and in fact defines) the Ullswater lineament at this point (Lineament 2 on Figure 6.17) so a steep northern margin is perhaps not surprising. However, the alternative model shown in Figure 7.12 is also considered feasible. Here the Wasdale outrop is interpreted as a northerly offshoot from the main Eskdale Granite. This would be compatible with the form of the metamorphic aureole around the Eskdale Granite, which extends northwards to encompass the Wasdale intrusion (Figure 1.3). It is, perhaps, possible that the passage of the Eskdale Granite magma to the surface was impeded by the presence of the Ennerdale Granophyre farther west (e.g. beneath profile AB) but extended northwards along the (concealed) eastern margin of the granophyre to form the Wasdale Granite. Alternatively, the interpretation shown in Figure 7.12 would be compatible with the concept that the Wasdale Granite represents the westernmost part of a separate component of the batholith concealed beneath the central Lake District (see Sections 7.9 and 7.10), but it is difficult to reconcile this with the form of the metamorphic aureole as mapped.

To the north of the Wasdale Granite, profile WX crosses the Crummock aureole between x = 12.5 and x = 15.5 km, and the eastern edge of the Ennerdale Granophyre between about x = 16.6 and x = 20 km. The same basic arrangement of intrusions as developed for profile AB proved to be a satisfactory basis for profile WX and is shown in the final models (Figures 7.11 and 7.12). Thus the Ennerdale Granophyre has to be relatively thin (1 - 2 km) and underlain by an intrusion of higher density (the Buttermere Granite, BMG) in order to fit the gravity anomaly. The roof of the granophyre lies beneath a thin layer of volcanics between about x = 20 and x = 23 km. The Crummock lineament (at around x = 14.5 km) is assumed to define the contact between the Buttermere Granite and the Loweswater Granodiorite. A satisfactory fit to the Crummock anomaly is achieved in terms of a high level granitic intrusion beneath the aureole.

The main feature on the southern flank of the gravity anomaly is the residual low in the Coniston area, between about x = 37 and x = 41 km (Feature CN, Figure 6.17). The detailed structure of the Borrowdale Volcanic Group in this area is complex but on a broad scale the sequence dips steeply to the south. The upper volcanics comprise the Airy's Bridge Formation overlain by composite formations DF and SFT (see Figures 1.3 and 1.7). These are all characterized by relatively low density values (2.70 to 2.74 Mg/m^3 respectively) and recent mapping (D. Millward pers. comm.) indicates that the sequence should be around 3 km thick in the region of the gravity low. Trial gravity modelling suggested that the volcanic sequence clearly contributes to the Coniston gravity low but that it is difficult to achieve a good fit without assuming either an underlying intrusion or a lower overall density for the volcanics.

Three solutions are considered feasible. The first is that shown in Figures 7.11 and 7.12 and assumes a small, deep-seated intrusion of density 2.66 Mg/m^3 (CNG) on the southern side of the Eskdale Granite, beneath the Coniston anomaly. The fit is reasonable, but not perfect, and could equally well be achieved by a deep-seated shoulder on the southern side of the Eskdale Granite rather than a separate intrusion. The second solution (Figure 7.13) shows that the Coniston low can be explained entirely in terms of an Upper Borrowdale Volcanic sequence around 2 to 3 km thick if the overall density of the sequence is 2.70 Mg/m^3 (i.e. equivalent to that of the Airy's Bridge Formation, see Section 5.5). The southern margin of the Eskdale Granite must also slope less steeply in this case than shown in Figures 7.12 and 7.13. The third solution (Figure 7.14) shows a very good fit to the Coniston low in terms of a small, high-level 'Coniston Granite' of density 2.62 Mg/m^3.

Which of these three interpretations is correct is a matter for debate. The fit in terms of a low density volcanic sequence is good (Figure 7.13) but the required density value of 2.70 Mg/m^3 is at the bottom end of the range of measured values for the Borrowdale Volcanic Group (see Section 5.5). Copper mineralization occurs in the Coniston area and is generally considered to be related to the southern margin of the granite batholith as defined by previous gravity models (e.g. Dagger 1977, Firman 1978). However, the gravity gradient is particularly steep along the southern side of the Eskdale Granite and the granite roof must plunge steeply south of around $x = 34$ km. A deep-seated intrusion on the southern side of the Eskdale Granite (Figures 7.11 and 7.12) could provide the source for the mineralization but a separate, high-level intrusion (Figure 7.14) produces the most

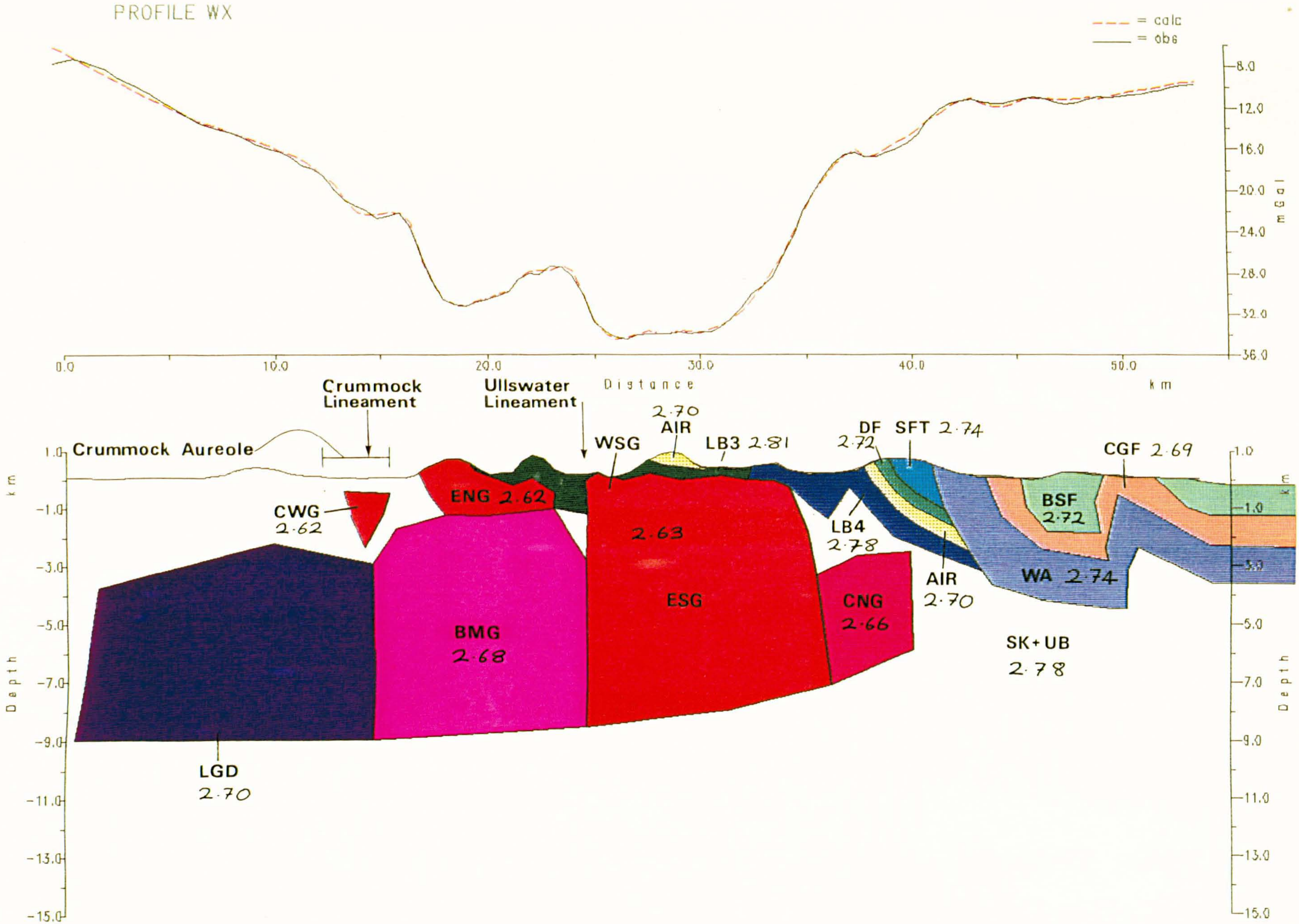


Figure 7.11 Interpretation along profile WX.

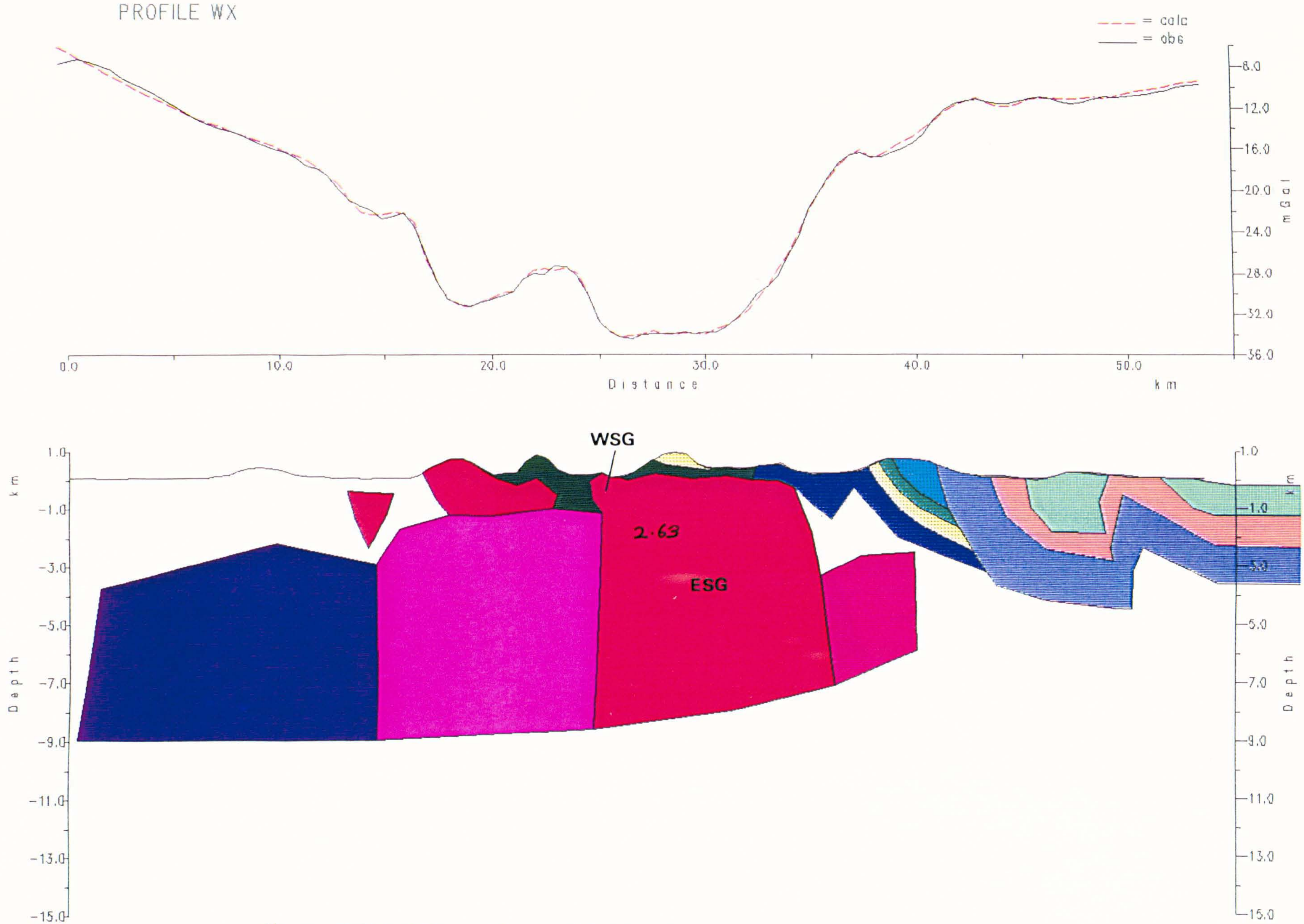


Figure 7.12 Alternative model for Wasdale Granite.

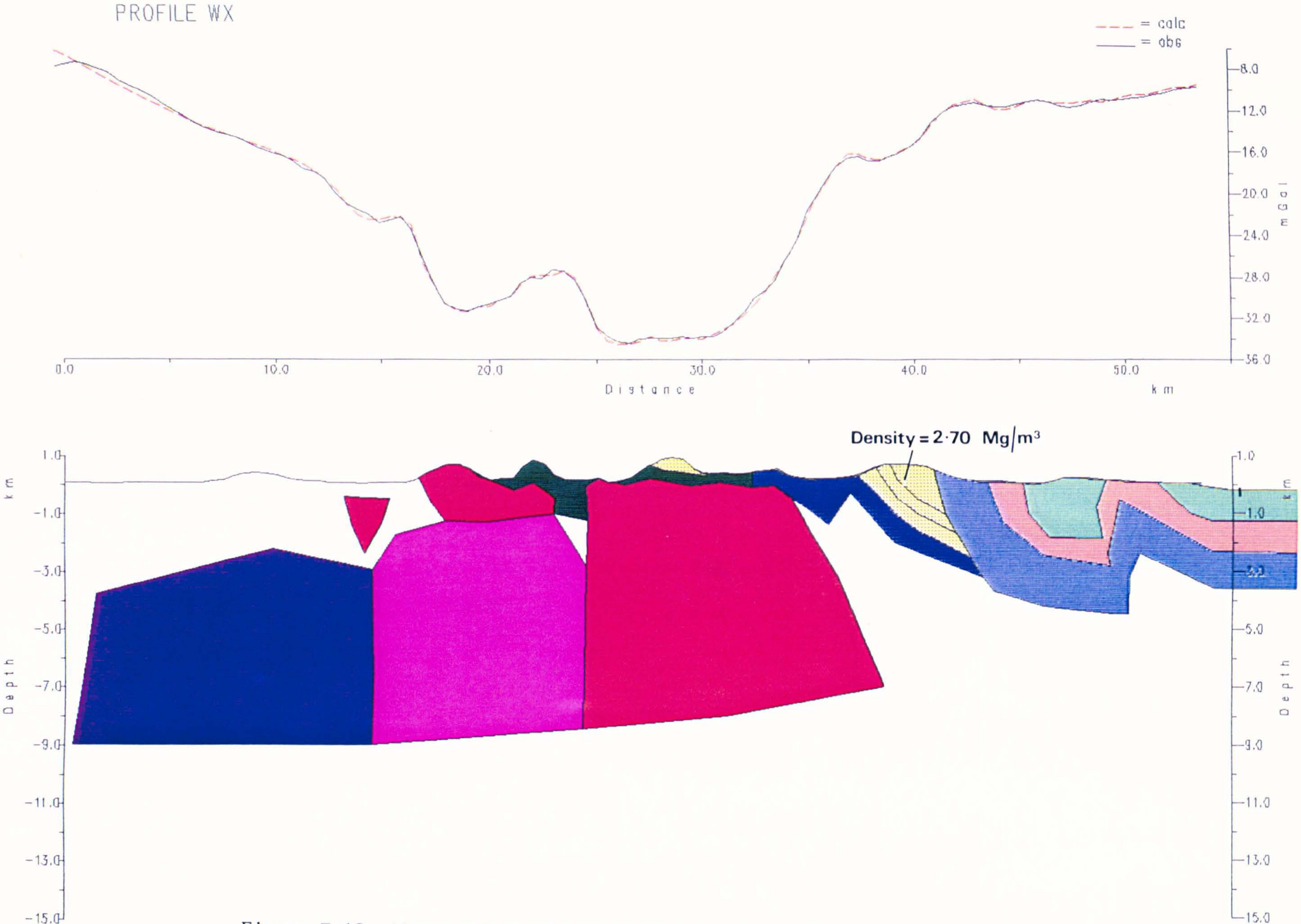


Figure 7.13 Alternative interpretation in the Coniston area assuming a low-density Upper Borrowdale Volcanic sequence.

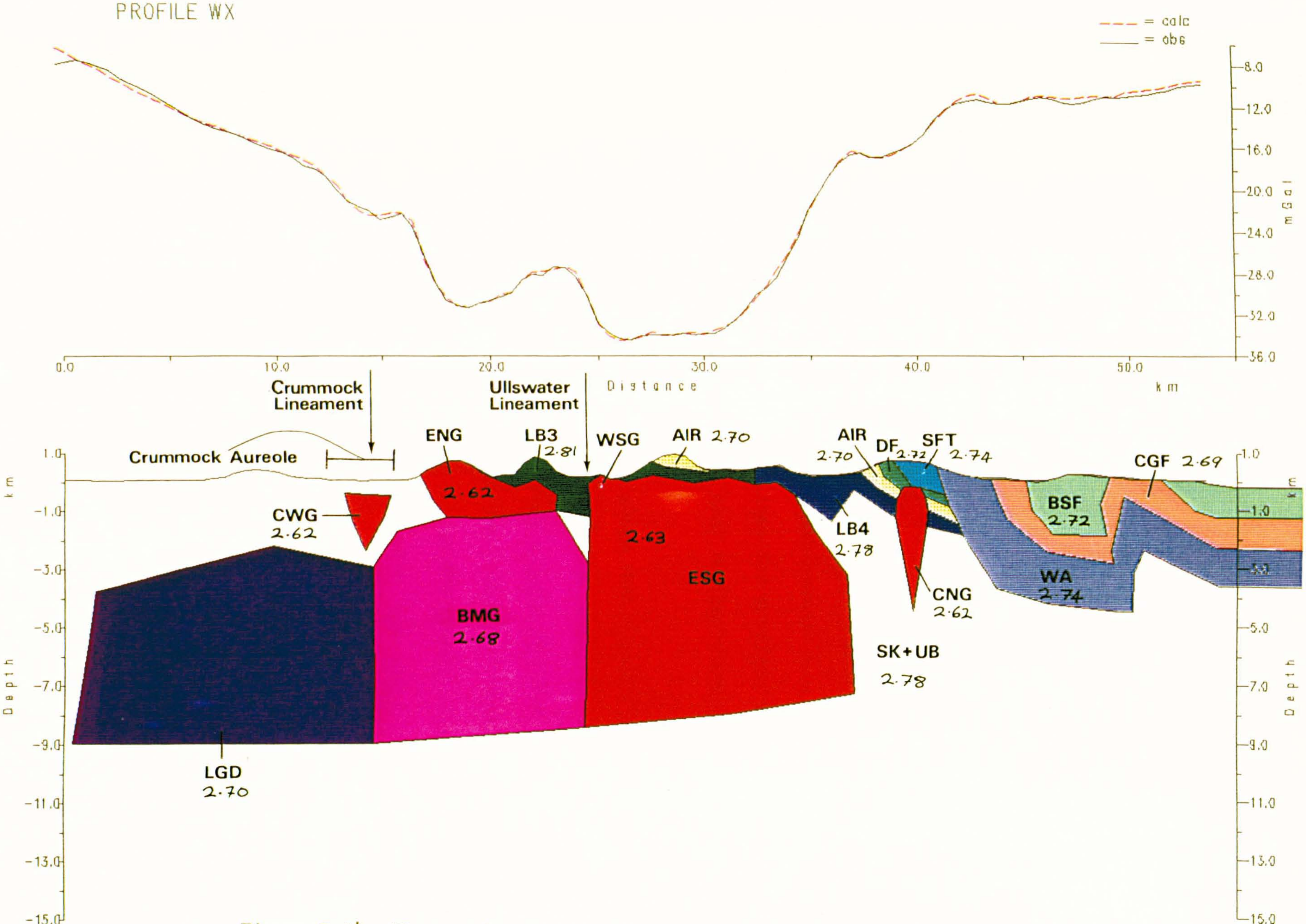


Figure 7.14 Alternative interpretation in the Coniston area assuming a high-level granitic intrusion.

satisfactory fit to the gravity data. It is also worth noting, however, that the Coniston gravity low is defined by relatively few gravity observations (see Figure 3.4) and a detailed survey would be required before more definitive modelling could be carried out.

7.6 TRAVERSE 11 (T11)

Detailed gravity traverse 11 was designed to investigate gravity gradients across the northern margin of the Ennerdale Granophyre and across the Crummock aureole at its widest point near Murton Fell. The northern end of the traverse is close to Lamplugh and it follows the only reasonable line of access across the Ennerdale Granophyre via the Ennerdale valley (Figure 7.1). The broad-scale form of the batholith has been taken from the models defined for profiles AB and WX and the interpretation concentrates on the near surface structures.

The final model (Figure 7.15) shows that a good fit to the gravity anomaly across the Crummock aureole is achieved in terms of a high-level granitic intrusion (CWG) at a depth of about 0.5 km directly beneath the aureole. The Ennerdale Granophyre is relatively thin, as defined previously, and the best fit to the gravity field is given if its base is not in direct contact with the underlying Buttermere Granite (BMG) at its northern end. As always, several variations are possible and the interpreted shape and depth extent of the Crummock and Ennerdale granites are critically dependent on the assumptions made regarding the underlying bodies. However, the interpretation shows that the overall arrangement of intrusions derived to fit the regional-scale profiles also works well at the detailed scale.

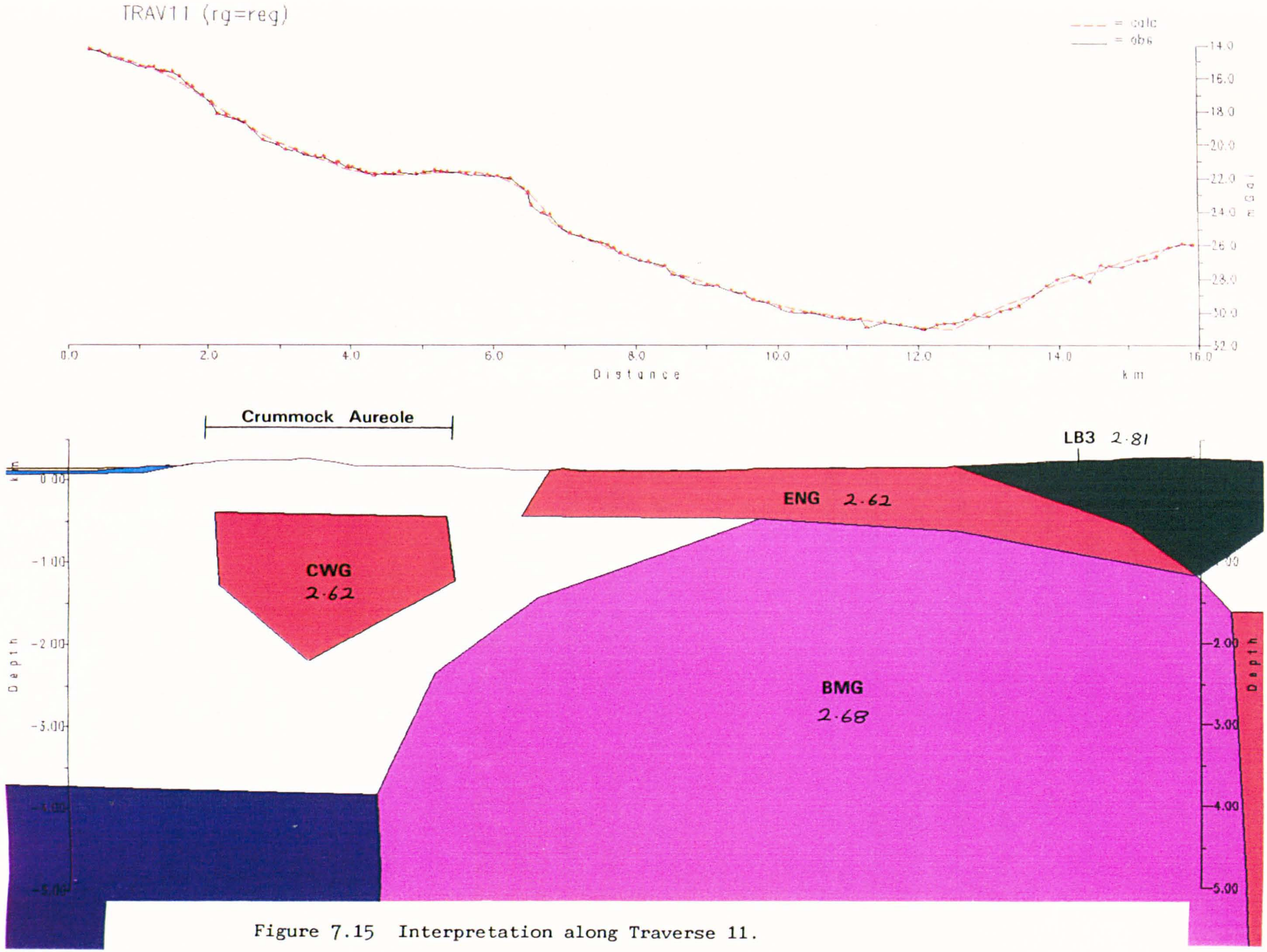


Figure 7.15 Interpretation along Traverse 11.

7.7 PROFILE KL and TRAVERSE 4/8 (T4/8)

Profile KL was positioned to investigate two separate aspects of Lake District structure. These are, firstly, the nature of the 'magnetic basement' across the western margin of the Lake District and, secondly, the relationship between the Eskdale Granite and the Eskdale Granodiorite. Gravity measurements were also made along two traverses (4 and 8, Figure 2.1) to examine the granite/ granodiorite relationship in more detail and these have been combined into a single profile for the purpose of interpretation (T4/8 on Figure 7.1). Three alternative interpretations of the form of the Eskdale Granodiorite are discussed (Figures 7.16 to 7.18) but the deeper structure is assumed to be the same in each case.

7.7.1 The magnetic Field

Profile KL lies to the west of the prominent magnetic anomaly associated with the Eycott Group and illustrates rather better than profile AB the shape of the long wavelength magnetic anomalies across the Lake District. Broad magnetic highs occur on the southern and northern margins with a broad low over the central Lake District (Figures 7.16 to 7.18). As along other profiles, a variety of interpretations is possible but the essential attributes of any model are that (a) magnetic rocks must be relatively deep-seated to fit the long wavelength anomalies, (b) 'magnetic basement' in the southern Lake District cannot be cut out abruptly by the Eskdale Granite/ Granodiorite but must extend northwards beneath the batholith, and (c) 'magnetic basement' must approach nearer to the surface again along the northern margin of the Lake District.

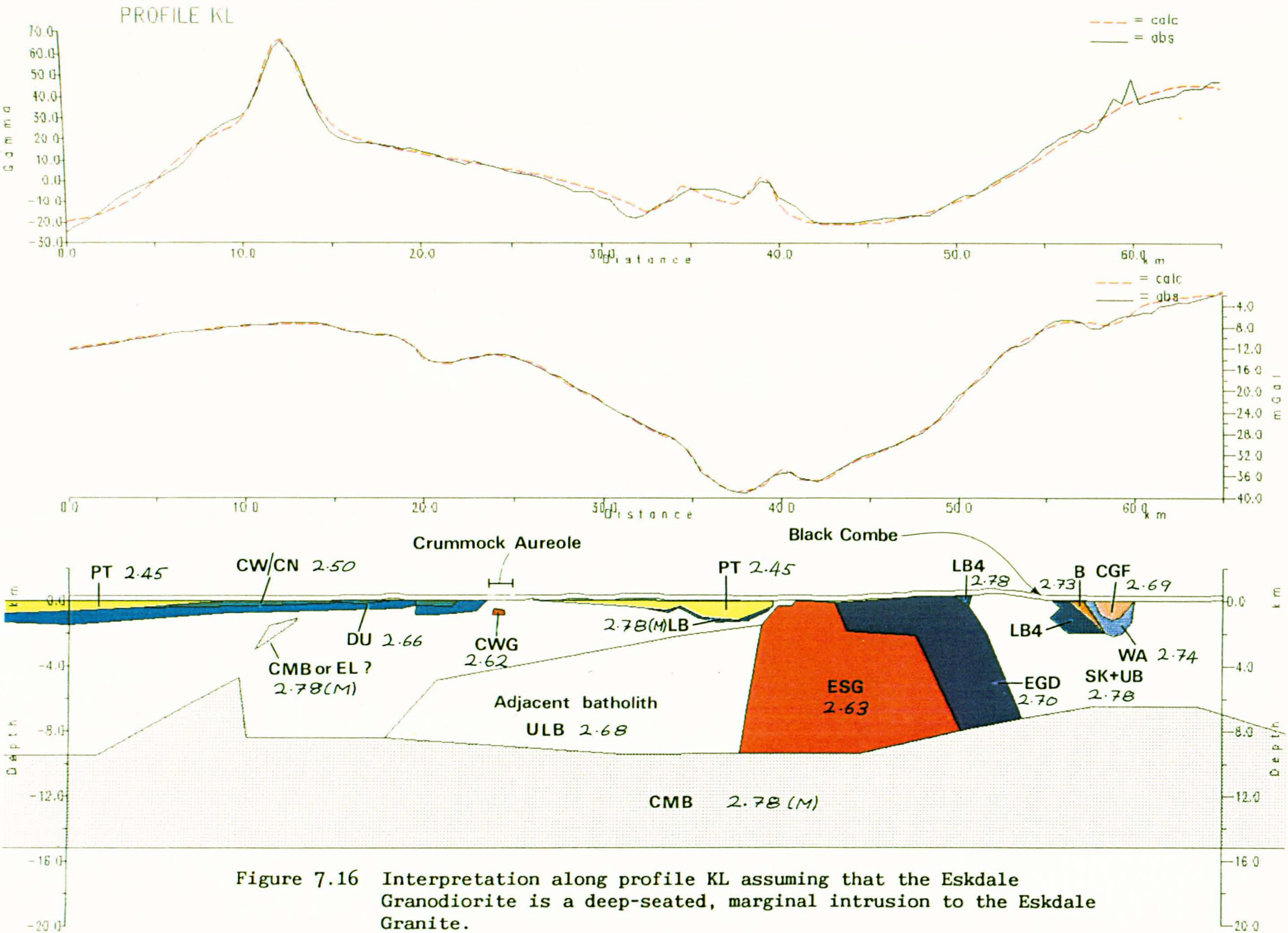


Figure 7.16 Interpretation along profile KL assuming that the Eskdale Granodiorite is a deep-seated, marginal intrusion to the Eskdale Granite.

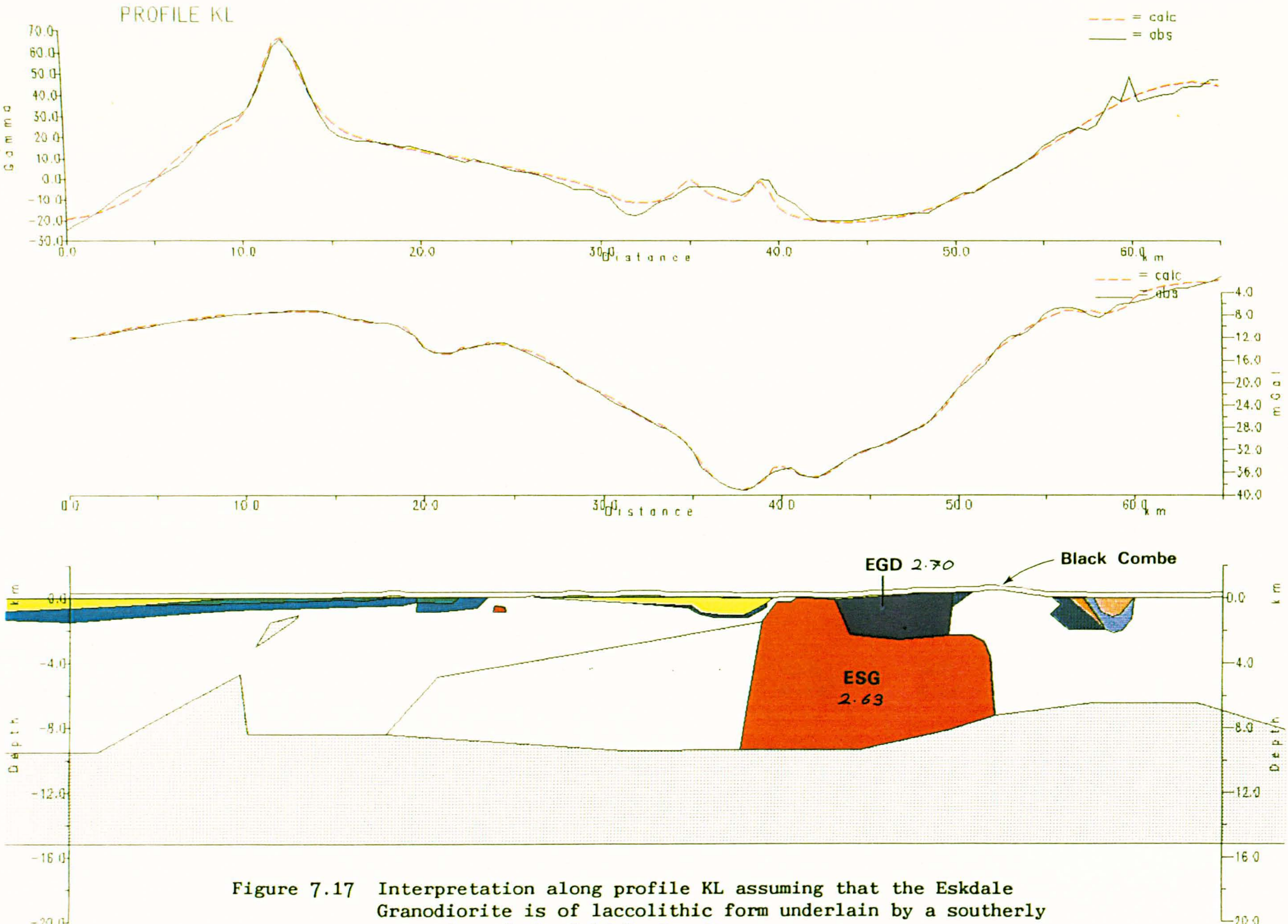


Figure 7.17 Interpretation along profile KL assuming that the Eskdale Granodiorite is of laccolithic form underlain by a southerly extension of the Eskdale Granite.

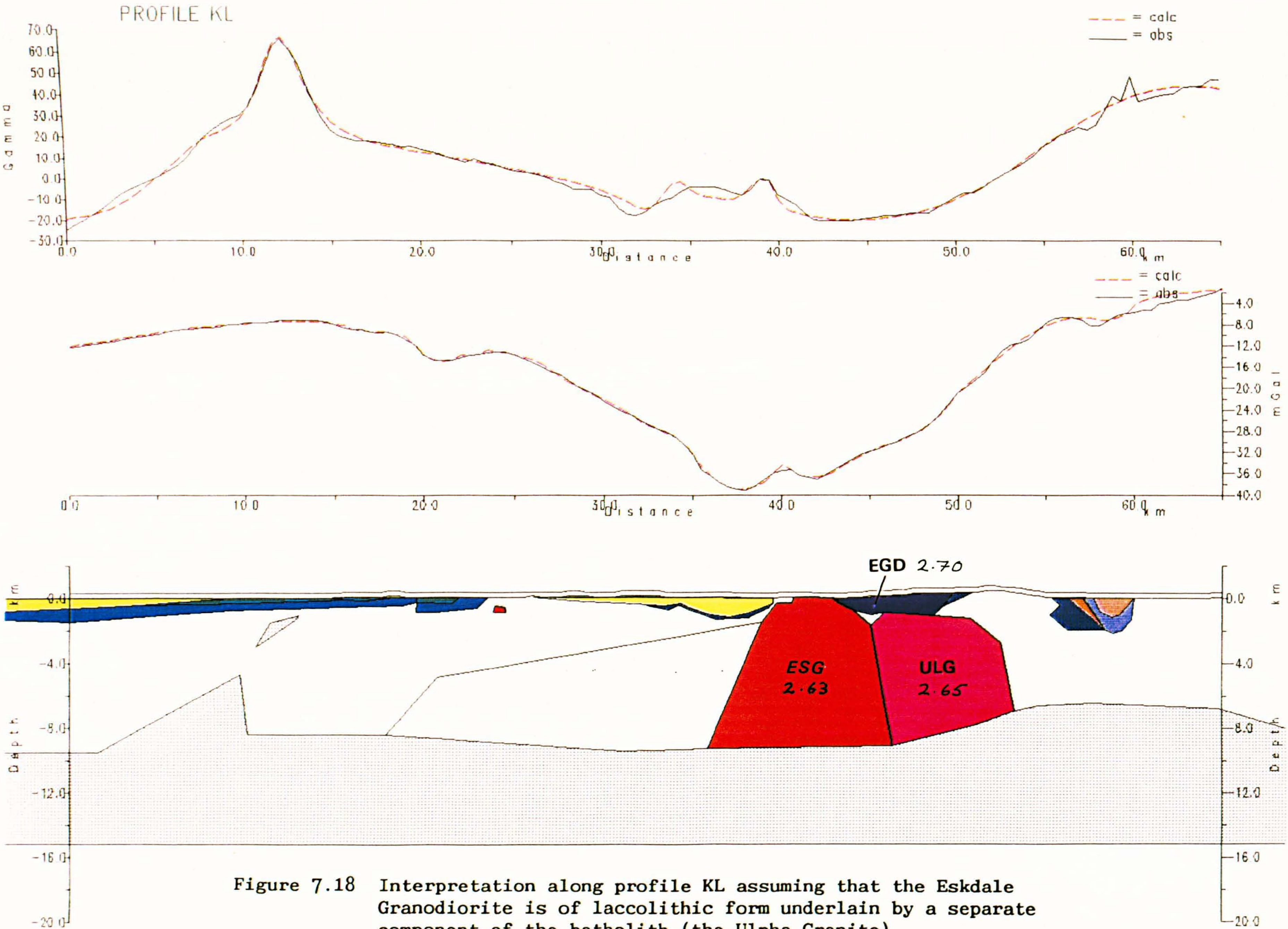


Figure 7.18 Interpretation along profile KL assuming that the Eskdale Granodiorite is of laccolithic form underlain by a separate component of the batholith (the Ulpha Granite).

The final interpretation for profile KL (Figures 7.16 to 7.18) assumes a magnetic basement of susceptibility 0.02 SI (CMB) extending downwards as far as the mid crust, as along profile AB. The basement reaches to within around 6 km of the surface at the southern end of the profile and dips northwards beneath the batholith. An area of poorly defined higher frequency magnetic anomalies occurs to the north of the Eskdale Granite outcrop, where the profile crosses non-magnetic Permo-Triassic sediments. Anomalies of similar amplitude occur over parts of the Borrowdale Volcanic sequence on other profiles but are insufficiently well defined by the regional magnetic data to allow definitive modelling. A layer of slightly magnetic Lower Borrowdale lavas (LB) beneath the Permo-Triassic seems the most likely explanation for the anomalies on profile KL and gives a reasonable fit to the magnetic field.

On the northern margin of the Lake District there is a shorter wavelength magnetic anomaly superimposed on the broader high at around x = 12 km. This has been modelled in terms of a small magnetic body lying at a depth of 1 to 2 km (labelled 'CMB or EL?' on Figure 7.16) and having the same magnetic susceptibility as the basement. The underlying basement reaches to within 5 km of the surface and dips northwards. Examination of the images of the magnetic field (Figures 6.6b and 6.9b) shows that the short wavelength high is one of a pair of sharp anomalies on the northwest coast of the Lake District which trend in an ENE direction (lineaments 14 and 15, Figure 6.17). It is not obvious whether they are related to the Eycott anomaly (to the north) or the broad magnetic high (to the west); the latter being part of the prominent magnetic high which extends between the northern Lake District and the Isle of Man (Figure 6.19) and which is presumably associated with the deep magnetic basement (see discussion in Section 6.8).

The relationship between the high-level body and the basement shown on figures 7.16 to 7.18 is suggestive of a south-directed thrust fault having emplaced a slice of basement material nearer the surface. Alternatively, although the anomaly lies well to the south of the main Eycott magnetic high, it lies along strike from the series of anomalies associated with the Eycott lavas on the eastern margin of the Skiddaw Group (lineaments 12 and 13, Figure 6.17) and it is possible that a similar arrangement exists on the western margin, concealed beneath the Carboniferous rocks.

7.7.2 The gravity field

The central section of profile KL, from around x = 20 to x = 40 km, runs along the western flank of the batholith, where two-dimensional modelling of the gravity field is inappropriate. The adjacent batholith is represented in the models by a body of density 2.68 Mg/m^3 (ULB on Figures 7.16 to 7.18) but neither its depth or density have any significance in terms of identifiable components of the batholith. Its purpose is to enable reasonable models for the overlying sedimentary sequences and the southern part of the batholith to be developed.

The gravity field is not well defined offshore at the northern end of the profile (i.e. north of x = 15 km) but it would appear that only a relatively thin Carboniferous and Permo-Triassic sequence is present. A short wavelength anomaly occurs around x = 21 km which is visible as a prominent residual gravity low on the shaded images (e.g.

Figure 6.9a, feature UC on Figure 6.17). Complex faulting occurs in the this area, with (low density) Upper Carboniferous and Permian rocks preserved in places (Eastwood et al. 1931)), and the most likely explanation for the anomaly is probably a thickened sedimentary sequence as shown in the models.

The profile crosses the Crummock aureole, at its extreme western end, between x = 24 and x = 25 km. The aureole is only 1 km wide at this point and no gravity anomaly is apparent from the regional data. The model shows a small, high-level granitic body beneath the aureole which serves only to demonstrate that a small intrusion could easily remain undetected by the regional gravity data. The Permo-Triassic sequence on the western margin of the Lake District cannot be definitively modelled from profile KL but the general form shown in Figures 7.16 to 7.18 is probably a reasonable approximation. Borehole data from the western margin of the Lake District (1:50K geological maps, sheets 37 and 47) shows the Permo-Trias directly overlying the Ordovician basement and thickening to a depth of around 1 km towards the coast in the Drigg area. The present interpretation suggests that the Permo-Triassic sequence thins rapidly north of around x = 35 km.

7.7.3 The Eskdale Granodiorite

Three alternative interpretations are given for the Eskdale Granite and Granodiorite along profile KL. Figure 7.16 shows an attempt to interpret the gravity field in terms of the granodiorite (body EDG, density 2.70 Mg/m^3) extending to depth along the southern side of the Eskdale Granite (ESG, 2.63 Mg/m^3). Although, at first sight, this might seem the most obvious solution, it is apparent that material of lower density than the granodiorite must extend southwards at shallow depth beneath the granodiorite outcrop. This is shown as a southwards extension of the Eskdale Granite on Figure 7.16 and the model implies that granite must underlie the granodiorite outcrop for almost two thirds of its extent. The fit is reasonably good, except over the change of gradient at around x = 47 km.

Figure 7.17 takes the concept of a relatively thin granodiorite a stage further by modelling the gravity anomaly in terms of a laccolithic body underlain by granite. A good fit has been achieved in terms of a granodiorite 2 to 3 km thick underlain by a shoulder of the Eskdale Granite extending southwards as far as Black Combe. However, such a large and flat-roofed extension to the Eskdale Granite seems out of proportion with the exposed part of the intrusion, and it is equally possible that an entirely separate component of the batholith lies beneath the granodiorite. Figure 7.18 shows a good fit in terms of a separate concealed intrusion of density 2.65 Mg/m^3 (i.e. a density between that of the Eskdale Granite and Granodiorite). Interpretations along profiles QR and AB also indicate that it is possible to explain the gravity field on the southern flank of the batholith in terms of a separate intrusion which is referred to as the Ulpha Granite.

The detailed gravity field across the Eskdale Granite and Granodiorite is defined by traverses 4 and 8 (combined here as T4/8). Interpretations in terms of a thin granodiorite underlain by either an extension of the Eskdale Granite or a separate intrusion (i.e. the Ulpha Granite) are shown in Figures 7.19 and 7.20 respectively. In the case of the former, the granodiorite is required to be around 2 km thick while, if it is underlain by a separate intrusion of slightly higher density than the Eskdale Granite, it may be only around 1 km

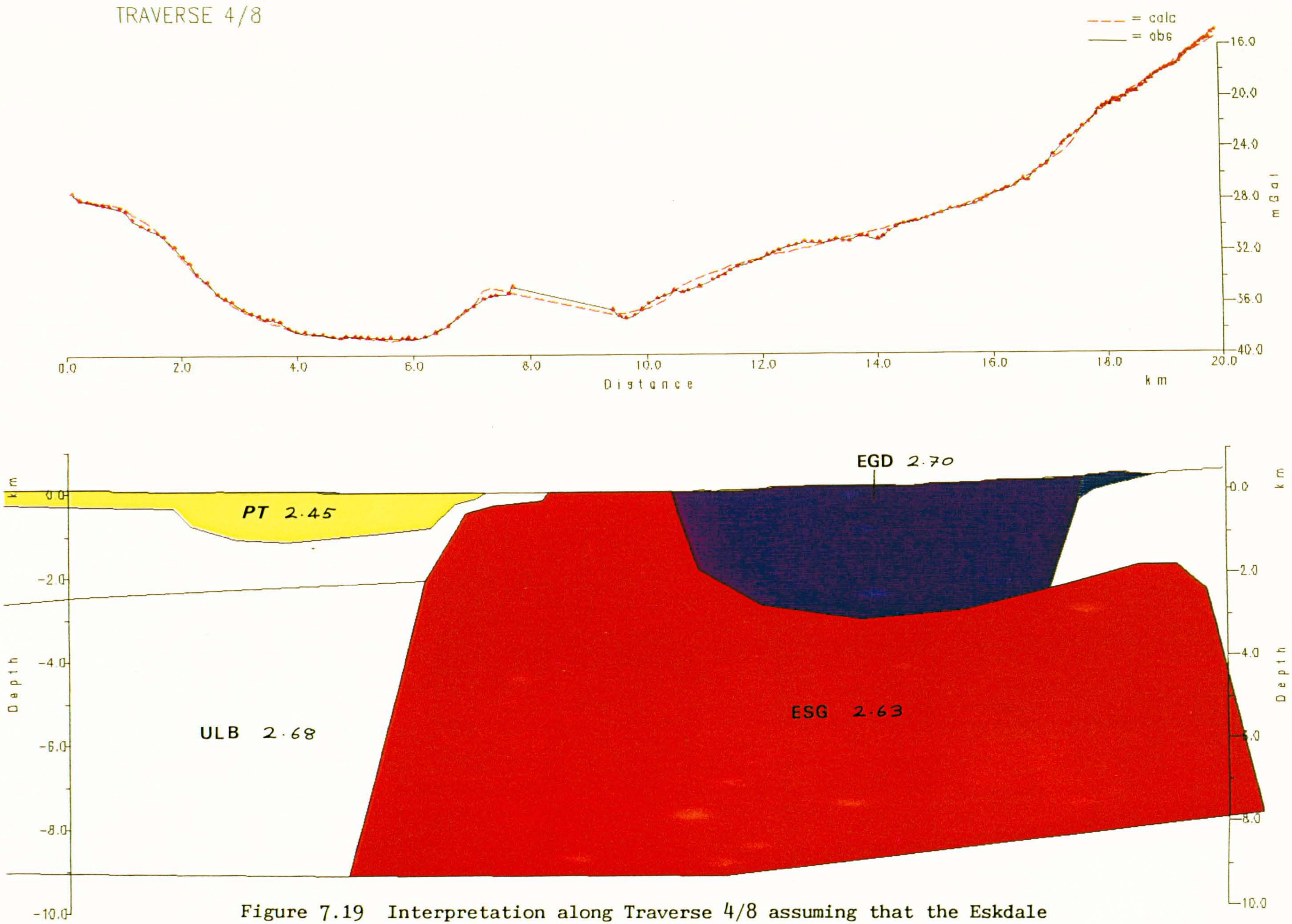


Figure 7.19 Interpretation along Traverse 4/8 assuming that the Eskdale Granodiorite is of laccolithic form underlain by a southerly extension of the Eskdale Granite.

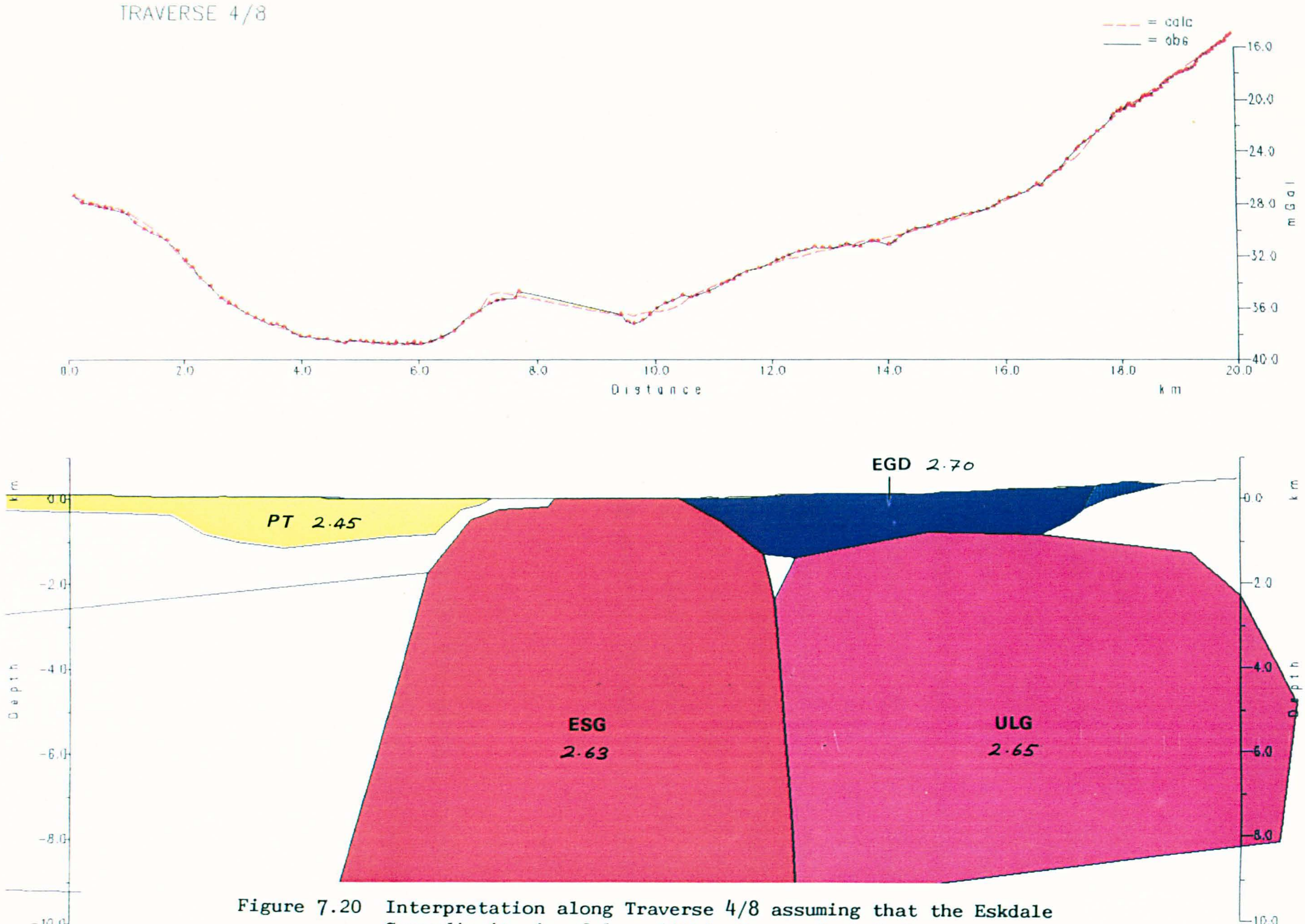


Figure 7.20 Interpretation along Traverse 4/8 assuming that the Eskdale Granodiorite is of laccolithic form underlain by a separate component of the batholith (the Ulpha Granite).

thick. Both models give a good fit to the gravity field at the detailed scale and also indicate that the margins of the granodiorite are near vertical or slope inwards.

The models described above are all based on the assumption that there are no major lateral density variations within the Eskdale Granodiorite. If this assumption is correct, then the models imply that the granodiorite is underlain by granite, at least at its northern end, and that it is quite possibly of laccolithic form. Interpretations in terms of an underlying southwards extension of the Eskdale Granite or a separate (Ulpha) intrusion give a marginally better fit to the gravity data than models which assume that the granodiorite extends to depth. Further evidence in support of a granite extending southwards beneath Black Combe comes from recent reports of high temperature mineralization and tourmaline veins at Black Combe which are best explained in terms of an underlying granitic intrusion (D.C. Cooper, BGS, pers. comm.).

7.8 PROFILE QR and TRAVERSE 3

Profile QR was positioned to examine (a) the southern margin of the Eskdale Granite and the Ulpha Syncline (over the ground between profiles KL and AB), and (b) the western end of the Crummock aureole (see Figure 7.1). Detailed gravity traverse 3 (T3 on Figure 7.1) crosses the Eskdale Granite about 2 km to the east of QR.

The axis of the Ulpha Syncline intersects profile QR at around $x = 36$ km. The Upper Borrowdale Volcanic sequence (formation groups AIR and UL, see Figures 1.3 and 1.7) presumably thickens into the syncline and then thins again towards the line of the Coniston Limestone unconformity (note also that point x = 40 km lies only 3 km east of the Black Combe inlier). The gravity gradient is very steep immediately to the south of the Eskdale Granite and then flattens southwards across the Ulpha Syncline (as on profile AB, Section 7.4). Two alternative interpretations are given in Figures 7.21 and 7.22 which probably represent the extremes of reasonable solutions. The former (Figure 7.21) shows the Ulpha Syncline underlain by a separate intrusion of density 2.65 Mg/m^3 (the Ulpha Granite (UG) as postulated for profiles KL and AB). The Upper Borrowdale Volcanic sequence is around 1.2 km thick at its maximum and has density values as defined in Section 5.5 (see also Table 7.1).

The alternative model (Figure 7.22) explains the gravity field in terms of a thickened volcanic sequence across the Ulpha Syncline without recourse to an underlying intrusion. In this case it is clear that the roof of the Eskdale Granite must extend southwards for some distance at a depth of around 2 km. The volcanic sequence needs to be around 2 km thick at the centre of the syncline and the most satisfactory fit to the observed field is achieved if the bulk density of the entire Upper Borrowdale Volcanic sequence is at the lower end of the measured range (i.e. 2.70 Mg/m^3). Both models include a concealed eastwards extension of the Eskdale Granodiorite on the southern margin of the Eskdale Granite although this could be replaced by a ridge on the underlying intrusion.

Figure 7.23 shows a detailed interpretation across the Eskdale Granite along traverse 3 (T3). The main purpose is to examine the southern and northern margins of the granite outcrop; the deeper structure is based on that shown in Figure 7.21. The gravity field is almost flat over the outcrop, which suggests that there are no major lateral density variations. The interpretation also indicates that both margins slope outwards at a relatively steep angle (> 45^{o}).

To the north of the Eskdale Granite profile QR runs along the western flank of the batholith. As on profile KL, 2-D modelling is invalid here and the adjacent batholith is represented by a body of density 2.68 Mg/m^3 (ULB on Figures 7.21 and 7.22). Its purpose is to enable realistic models to be developed for other parts of the profile and neither the depth nor the density of this body have any significance in terms of components of the batholith identified along other profiles.

There is a prominent secondary gravity low on the northern flank of the broad negative anomaly, from about x = 5 to x = 12 km (Figures 7.21 and 7.22). The same feature was noted on profile KL at around x = 20 km (Figures 7.16 to 7.18) and was explained satisfactorily in terms of a slightly thickened Carboniferous sequence. However, on profile QR it is clear that the southern edge of the anomaly lies well within the Skiddaw Group outcrop and, more importantly, coincides with the point where the profile crosses the Crummock aureole between x = 10.7 and x = 12 km. The anomaly cannot be explained, therefore, entirely in terms of a thicker Carboniferous sequence and Figures 7.21 and 7.22 show a separate high level granitic intrusion - presumably the western end of the Crummock Granite.

In the light of this interpretation, the possibility should be considered that the corresponding anomaly on profile KL is due to the same body (i.e. the Crummock intrusion), rather than a thickened

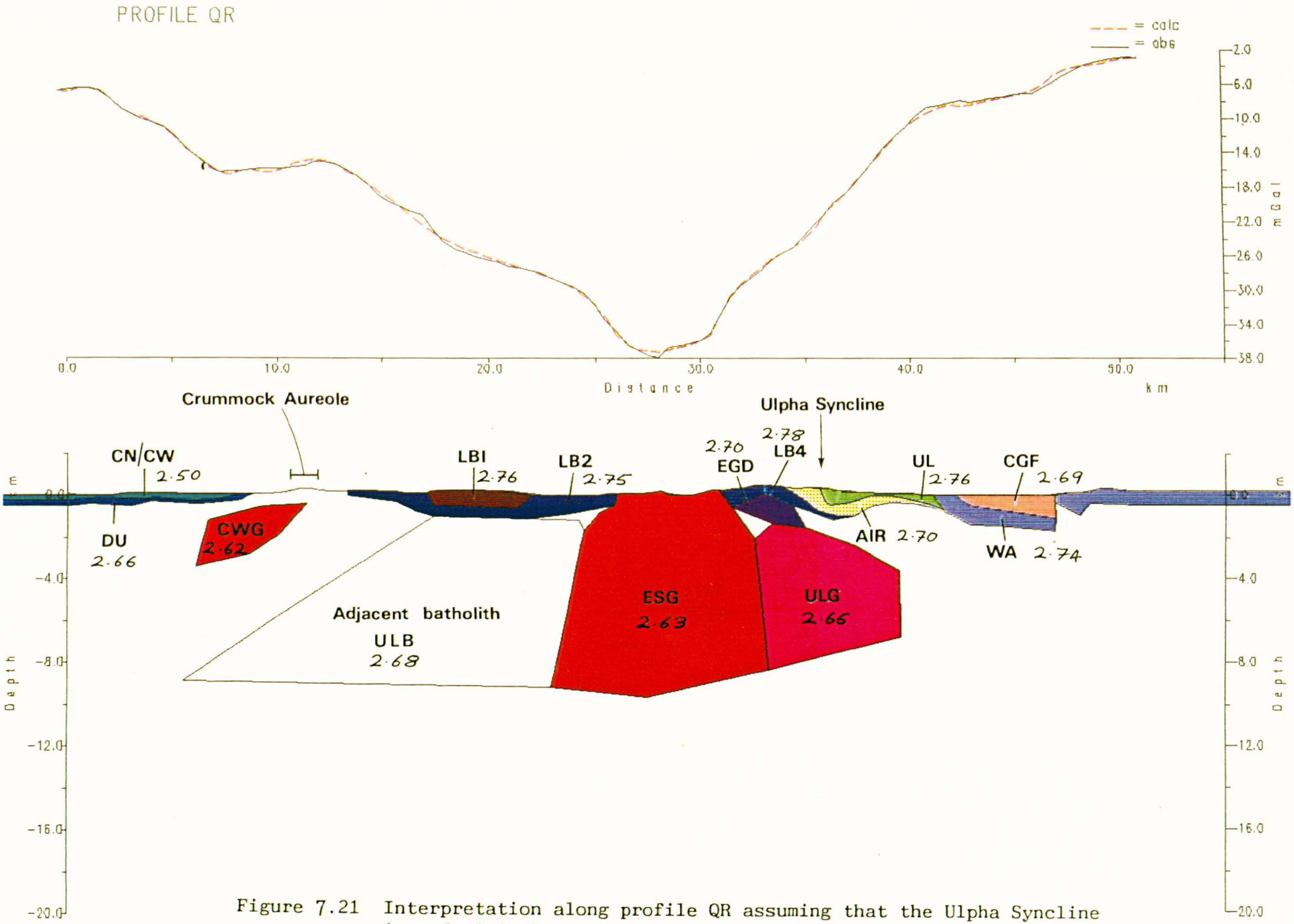


Figure 7.21 Interpretation along profile QR assuming that the Ulpha Syncline is underlain by a separate component of the batholith (the Ulpha Granite).

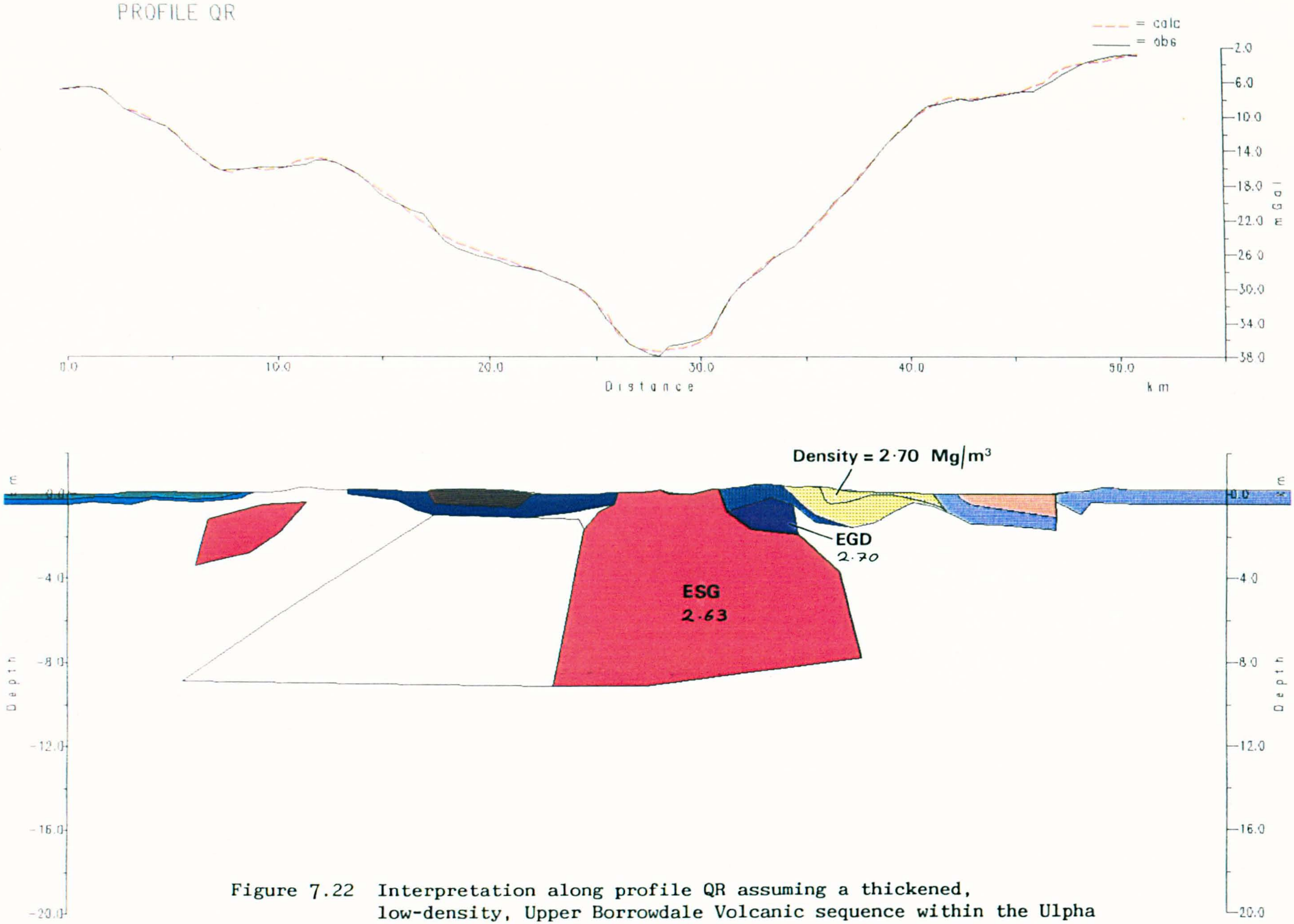


Figure 7.22 Interpretation along profile QR assuming a thickened, low-density, Upper Borrowdale Volcanic sequence within the Ulpha Syncline.

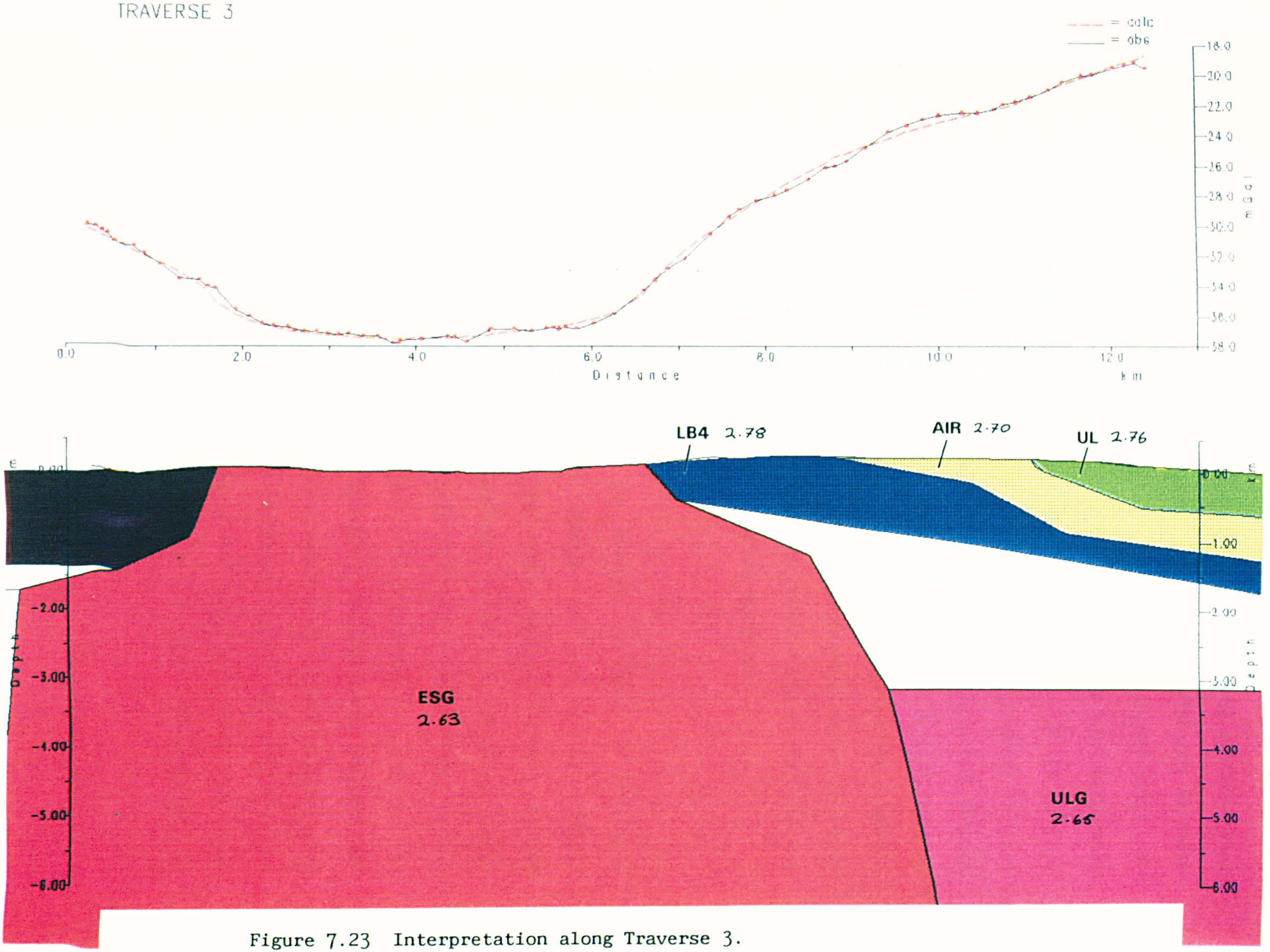


Figure 7.23 Interpretation along Traverse 3.

Carboniferous sequence. The presence of the Crummock aureole across both profiles would tend to support this. However, the shaded-relief images of the gravity data (e.g. Figure 6.9a) suggest that the residual low over the Carboniferous rocks (feature CU, Figure 6.17) is identifiable as a separate anomaly from the residual low associated with the Crummock aureole (feature CW, Figure 6.17). It is perhaps possible that the gravity field in this area is too complex for 2-D modelling and the anomaly on profile QR represents the combined effects of the NW margin of the deeper batholith, the NW margin of the Ennerdale Granophyre, the western end of the Crummock Granite together with effects of low density Carboniferous and Permo-Triassic rocks to the north and west. The structure might be resolved by a detailed 3-D model together with more detailed geological control.

7.9 PROFILE CD

Profile CD was positioned to address a number of separate problems. In the north it passes through the site of the Silloth borehole [NY 12306 54849] which provides valuable control on the thickness of the Permo-Triassic sequence in the western part of the Carlisle Basin (see Figures 5.27 and 5.28). It passes close to the maximum of the Eycott magnetic anomaly and traverses the central part of the Lake District where the batholith is concealed beneath the Borrowdale Volcanic Group, just to the east of the Eskdale Granite. At its southern end it traverses the centre of one of the main magnetic highs in the southern Lake District (anomaly CM Figure 6.17). The final models, including a number of alternatives for specific parts of the profile are shown in Figures 7.24 to 7.33.

7.9.1 The concealed batholith

Overall, the central negative gravity anomaly across the concealed batholith on profile CD is strongly asymmetrical, with a steeper gradient on the southern side than on the northern side. Bott (1974 and 1978) explained the asymmetry in the western part of the batholith in terms of a fine density zonation (his profile AA) but in the central Lake District he modelled the concealed batholith in terms of three major components increasing in density to the north (his profile BB). The final interpretation for profile CD (Figure 7.24) is in broad agreement with Bott's profile BB except that two of the major components have been correlated with batholith components previously identified on profile AB (Section 7.4). Thus the component identified on profile AB as the Buttermere Granite (BMG), also underlies the ground between the Crummock and Ullswater lineaments on profile CD ($x = 50$ to $x = 60$) and the Loweswater Granodiorite (LGD) lies to the north of the Crummock line.

South of the Ullswater lineament, profile CD crosses the Scafell Syncline (at $x = 63$ km). A separate residual gravity low was recognized from the image processing in this area and referred to as the Dunmail anomaly (DM Figure 6.17). It was suggested in Section 6.7 that the spatial correlation of residual gravity lows with broad synclines in the Borrowdale Volcanic Group might be due either to thick sequences of low density volcanic rocks or to underlying components of the batholith. This point was discussed in relation to the Ulpha Syncline in Sections 7.4 and 7.8 above (profiles AB and QR). However, in the case of the Dunmail low the presence of a large granitic intrusion beneath the Scafell Syncline is unavoidable because it coincides with the maximum negative gravity anomaly. The point at issue, however, is whether this intrusion is simply an eastwards continuation of the Eskdale Granite or an identifiably separate component of the batholith.

Models supporting both cases are feasible and it is not possible to give a definitive answer on the basis of the available geophysical information alone. In general it has proved easier to achieve a fit to the gravity data (along this and other profiles) if the underlying intrusion is assumed to reach quite close to the surface (around 1 km) rather than being more deeply buried. This in turn implies either that the batholith thins to the east or increases in density from the value of 2.63 Mg/m^3 measured for the Eskdale Granite (or both). On balance, it was felt that a separate intrusion of higher density (2.66 Mg/m^3) enabled marginally more acceptable models to be developed and was more compatible with the presence of a recognizable residual gravity low. It is postulated, therefore, that the Dunmail low corresponds to a separate intrusion (or phase of the batholith) of slightly higher density than the Eskdale Granite, henceforth referred to as the Dunmail Granite (DMG Figures 7.24 and 7.25). It lies beneath the Scafell Syncline, between the Ullswater lineament and lineament 4 (see Figure 6.17), and forms part of the main granite ridge underlying the central Lake District. Large density variations occur within the overlying Borrowdale Volcanic rocks, principally between the lower volcanics (formation LB3, 2.81 Mg/m^3) and the Airy's Bridge Formation (AIR, 2.70 Mg/m^3). The model suggests that these account for most of the short wavelength gravity anomalies across the Borrowdale volcanics and that the underlying Dunmail intrusion has a relatively flat roof reaching to within about about 1 km the surface.

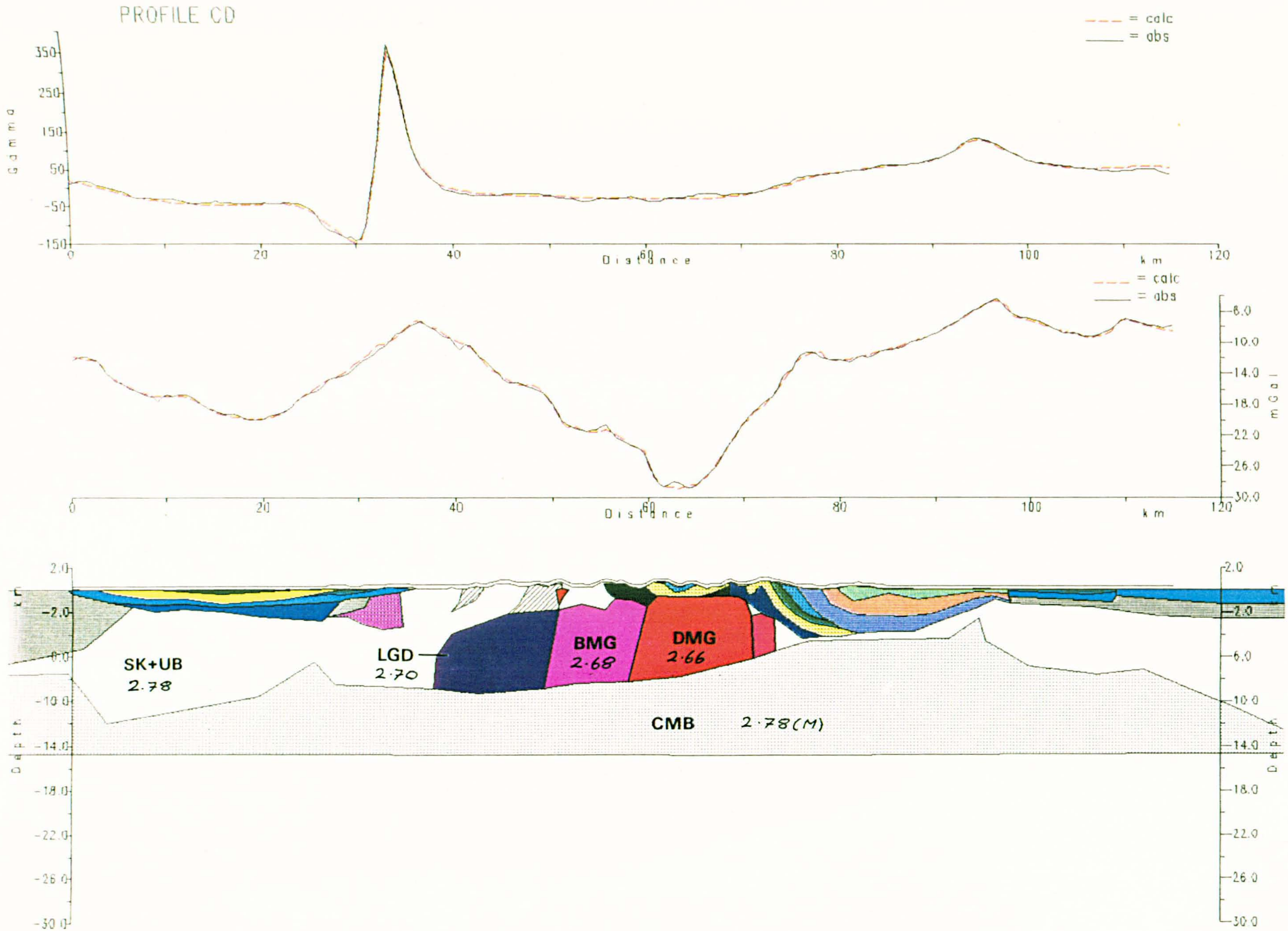


Figure 7.24 Interpretation along Profile CD.

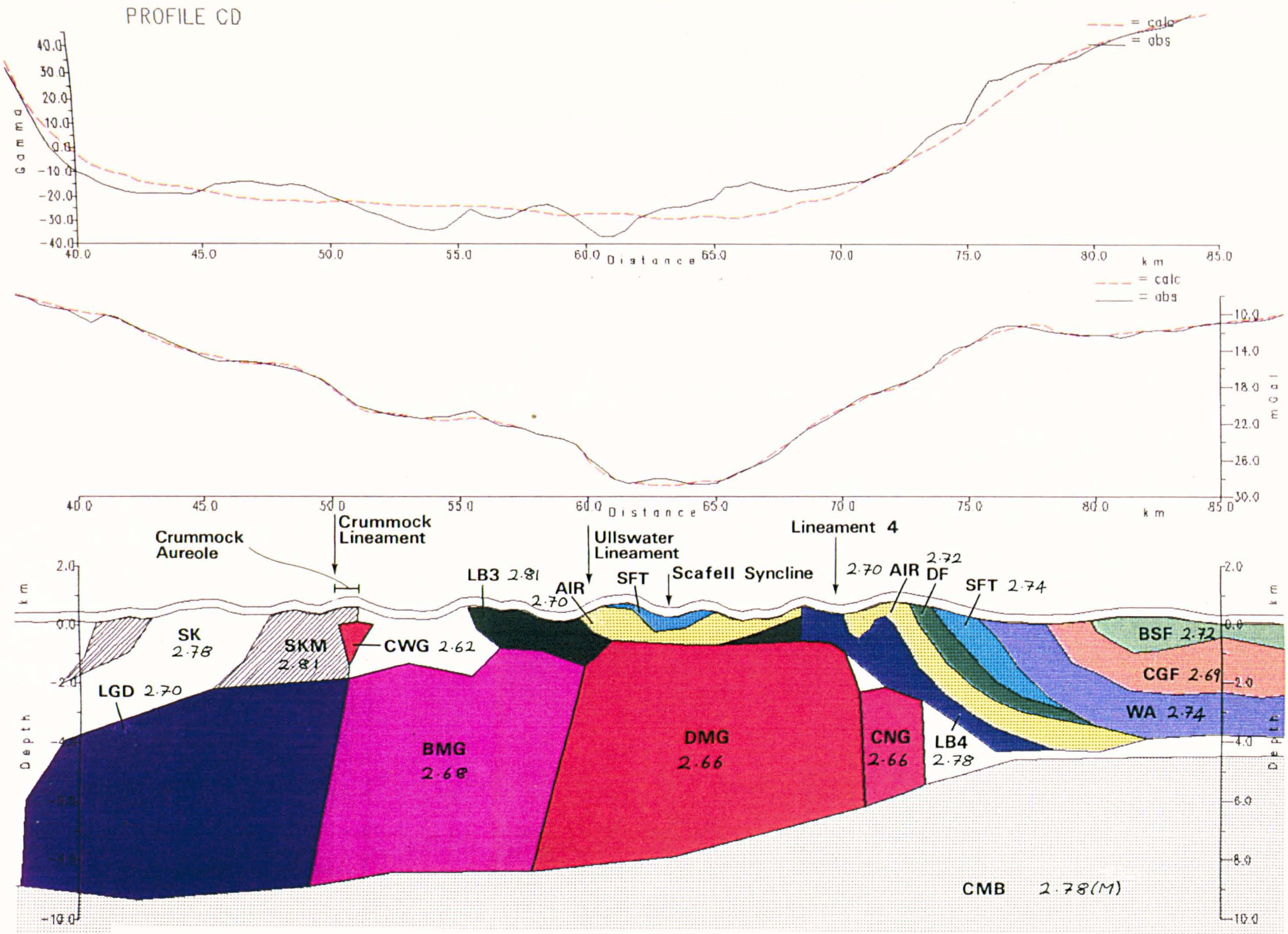


Figure 7.25 Central part of CD.

Profile CD crosses the extreme eastern end of the Crummock aureole between x = 50 and x = 51 km (Figure 7.25). As for profile AB, some modelling was carried out for the earlier multidisciplinary study of the aureole along a closely adjacent profile (Cooper et al. 1988, Figure 15; reproduced here as Figure 7.26). Like the previous interpretation, the present model explains the Crummock anomaly in terms of a small, high level, low density intrusion but it differs in one important respect. The residual negative gravity anomaly associated with the aureole extends from x = 50 to x = 55 km on profile CD. The previous interpretation explained this solely in terms of the Crummock intrusion which, therefore, had to lie mainly to the south of the mapped aureole to achieve a fit to the gravity anomaly (Figure 7.26). It is possible, however, to achieve an equally good fit with a smaller granitic intrusion underlying the aureole together with a contrast in the bulk density of the Skiddaw Group on either side of the Crummock Lineament (Figure 7.25).

As explained in Section 5.6 (Table 5.8), densities within the Skiddaw Group vary from around 2.72/2.73 Mg/m^3 for sandstones in the Loweswater Formation up to 2.81 Mg/m^3 for mudstones in the Kirkstile and Hopebeck formations. A value of 2.78 Mg/m^3 was calculated as a representative bulk density for the known sequence and was adopted as the background density for the modelling. The folded and faulted nature of the Skiddaw Group makes it difficult to estimate localized variations in bulk density across the outcrop, but the existence of such variations would seem quite likely, especially in relation to the Crummock line which has been identified as an important geological and geophysical lineament.

Geologically, the Crummock line separates two distinct tracts within the Skiddaw Group. To the south, where the lower part of the pile is considered to have been slumped and redeposited in the Llanvirn (Webb & Cooper 1988, see Section 1.2.1), the mean bulk density of the Skiddaw Group (2.78 Mg/m^3) would seem an appropriate value to use. Immediately to the north, however, where mudstones and siltstones predominate at outcrop, a higher density of up to 2.81 Mg/m^3 is probably more representative. When a body representing a zone of higher density mudstones is incorporated into the model (body SKM), the resulting form of the Crummock intrusion on profile CD (Figure 7.25) is considered to be more consistent with the mapped position of the aureole than that shown in the previous interpretation (Figure 7.26). The existence of such a contrast across the Crummock line also helps to explain the shape of the gravity field along other profiles (see below).

North of the Crummock line, small changes in gravity gradient can be modelled in terms of either undulations in the roof of the underlying granodiorite or further lateral density changes within the Skiddaw Group. The latter are perhaps more likely, and the preferred interpretation shows a slice of denser material between $x = 40.5$ and $x = 43$ km to illustrate the point (in practice both positive and negative contrasts with respect to the average density of 2.78 Mg/m^3 are likely to occur). The available gravity and density data are not sufficiently detailed to resolve structures within the Skiddaw Group more finely, but the present interpretation is consistent with the concept of a series of folds and (southwards directed ?) thrusts as indicated by recent mapping.

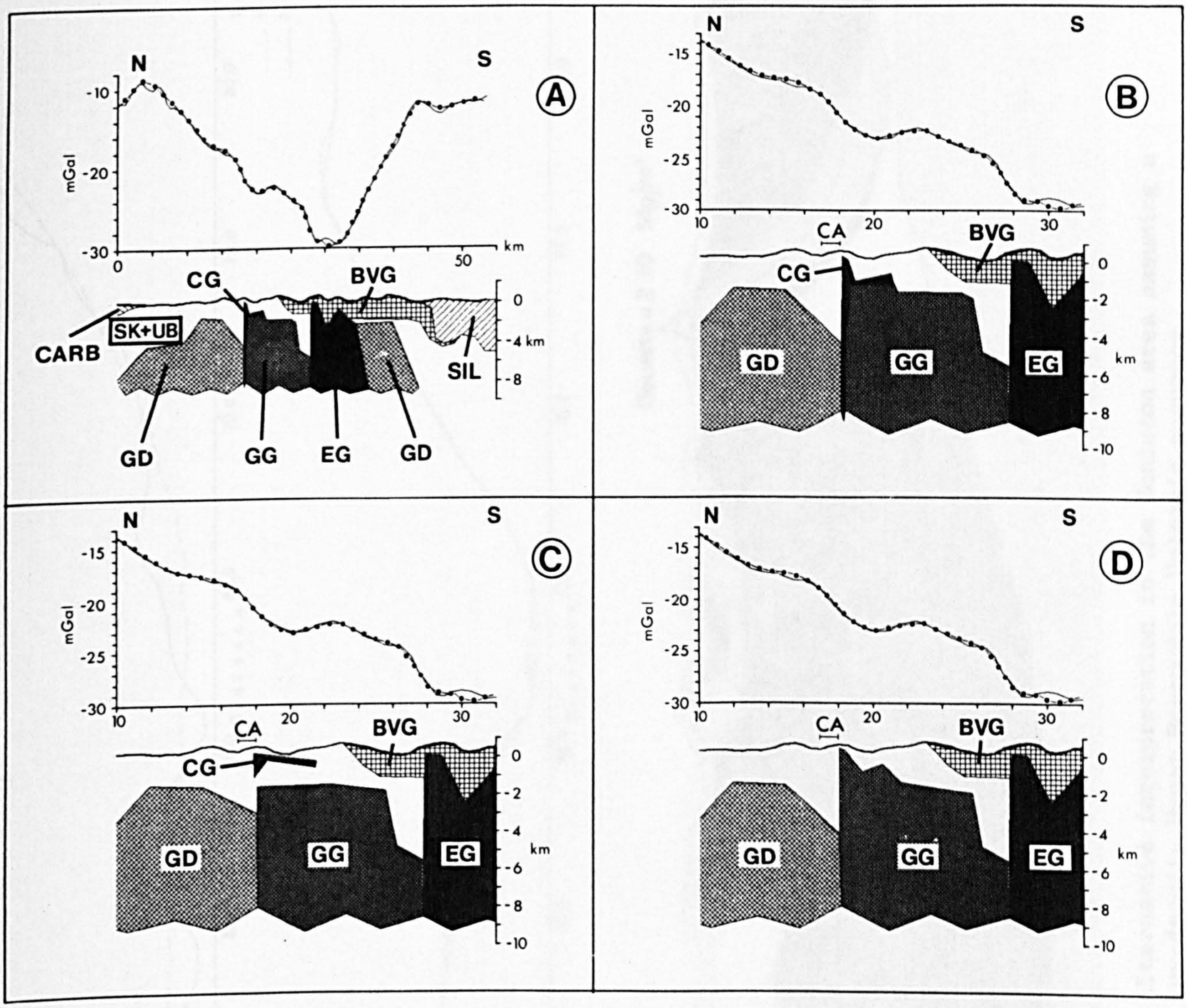


Figure 7.26 Gravity interpretation across the Crummock aureole from Cooper et al. (1988) - their section 2 (B shows details of model A in the region of the Crummock Aureole, C and D show alternative models for the Crummock anomaly). The codes shown on this figure differ from those used elsewhere in this work - they are translated as follows: BVG = Borrowdale Volcanic Group undivided, CA = Crummock Aureole, Carb = Carboniferous undivided, CG = Crummock Granite (CWG), EG = Eskdale Granite (ESG), GD = Loweswater Granodiorite (LGD), GG = Buttermere Granite (BMG), SIL = Silurian undivided, SK = Skiddaw Group, UB = basement undivided.

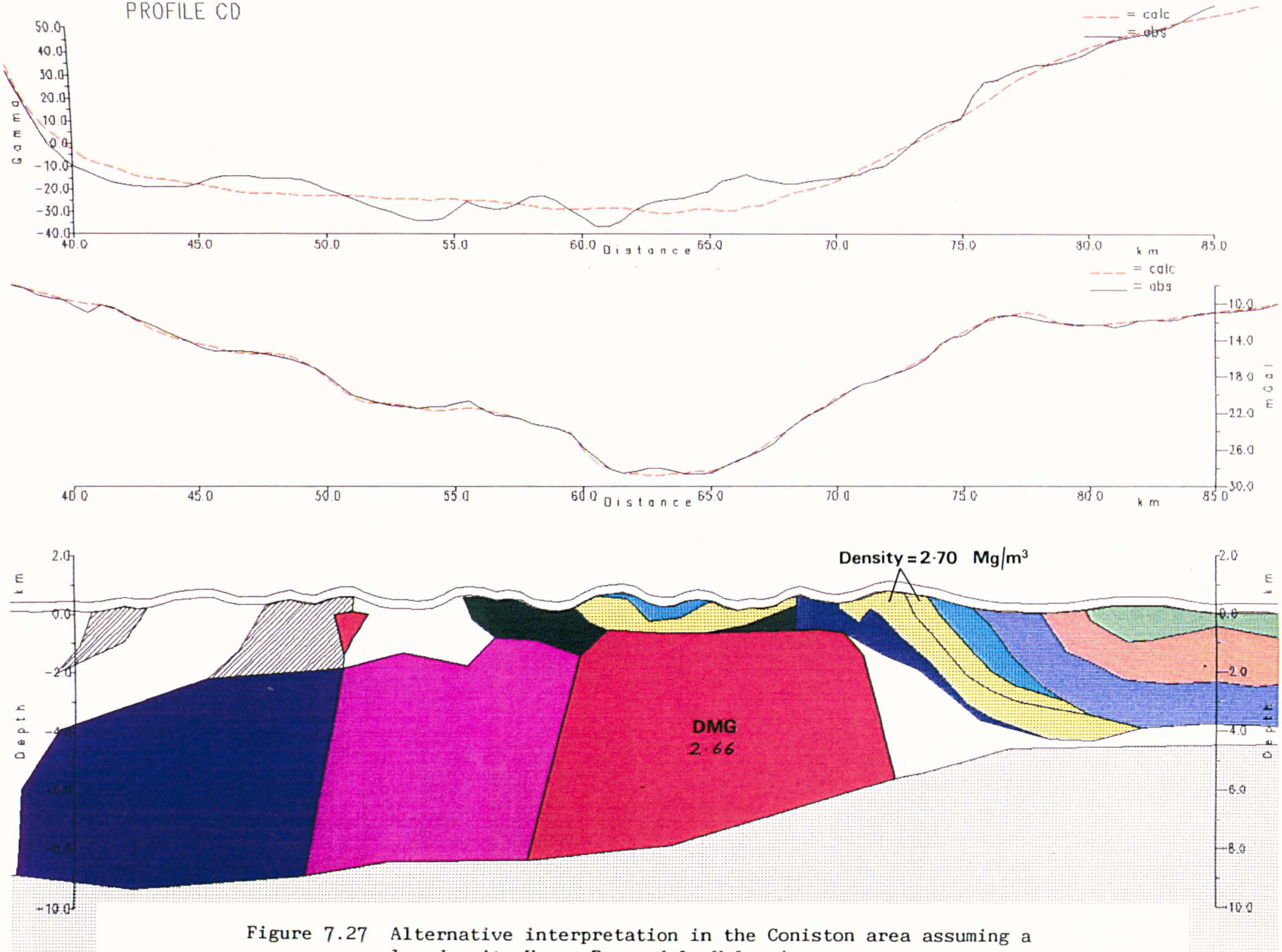


Figure 7.27 Alternative interpretation in the Coniston area assuming a low-density Upper Borrowdale Volcanic sequence.

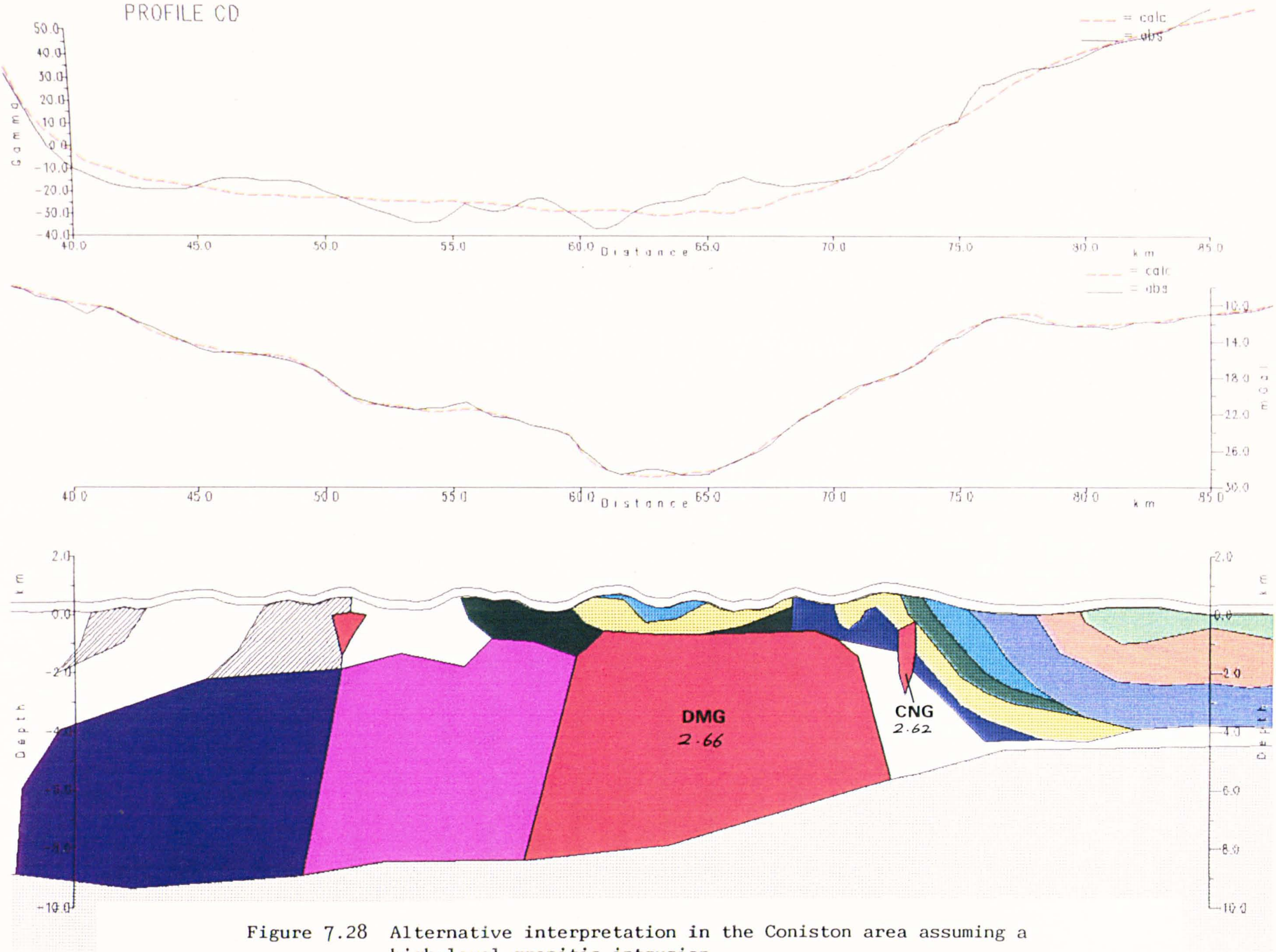


Figure 7.28 Alternative interpretation in the Coniston area assuming a high-level granitic intrusion.

On the southern flank of the batholith the gravity gradient is relatively steep, with a slight inflection centred around x = 73 km. This corresponds to the eastern edge of the Coniston residual gravity low identified from the image processing (CN, Figure 6.17). This anomaly was discussed in some detail in relation to profile WX (Section 7.5) and similar models give a reasonable fit to the gravity field along profile CD. As for profile WX, three solutions are considered feasible. The first is that shown in Figures 7.24 and 7.25 and assumes a small, deep-seated intrusion of density 2.66 Mg/m^3 (CNG) on the southern side of the Dunmail/Eskdale Granite, beneath the Coniston anomaly. The fit is reasonable but could equally well be achieved in terms of a deep-seated shoulder on the southern side of the Dunmail/Eskdale Granite rather than a separate intrusion. The second solution (Figure 7.27) shows that the Coniston low can be explained entirely in terms of the Upper Borrowdale Volcanic sequence if the density of formation DF (see Figure 1.7) is 2.70 Mg/m^3 rather than 2.72 Mg/m^3 (i.e. equivalent to that of the Airy's Bridge Formation). The southern margin of the Dunmail/Eskdale Granite must also slope less steeply in this case than shown in Figures 7.24 and 7.25. The third solution (Figure 7.28) shows a good fit to the Coniston low in terms of a small, high-level 'Coniston Granite' of density 2.62 Mg/m^3 similar to that shown in Figure 7.14 for profile WX. The relative merits of these models will be discussed further in Chapter 8.

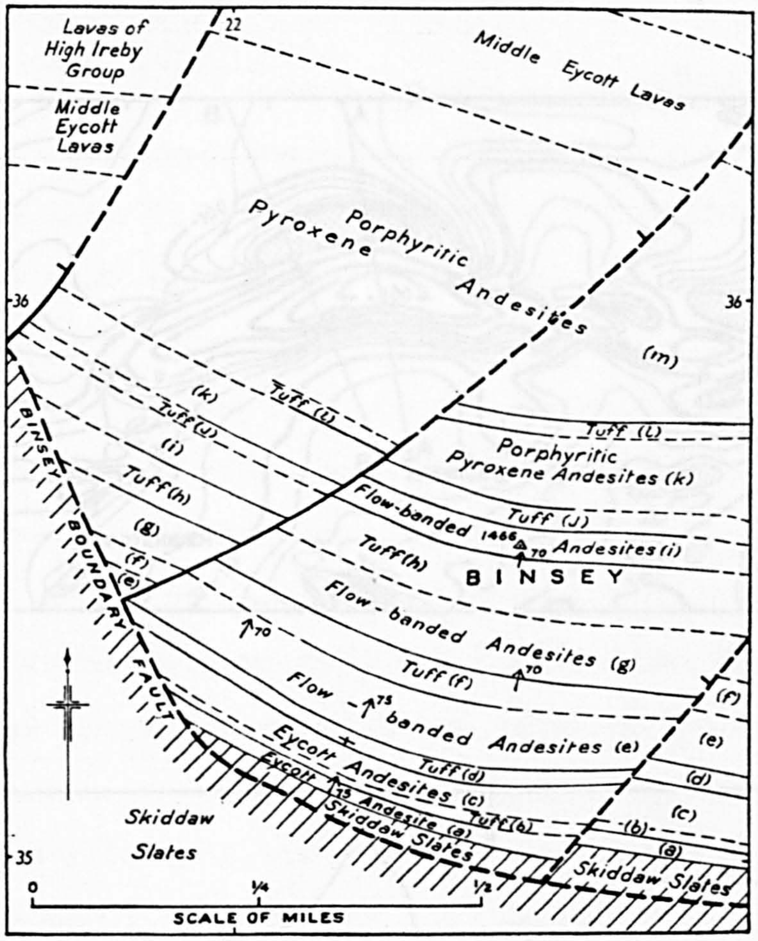
7.9.2 The northern part of profile CD

Profile CD crosses the magnetic anomaly associated with the Eycott Group at around x = 34 km. The Eycott Group comprises about 2500 m of basaltic and andesitic lavas with some acid lavas and tuffs (Eastwood et al. 1968)) and are divided into a lower (Binsey) formation and upper

(High Ireby) fomation. In the main outcrop at Binsey, just to the east of profile CD, they generally dip steeply northwards at around 70^{o} (Briden and Morris 1973) but in places are almost vertical or overturned to the south (Eastwood et al. 1968 and Figure 7.29b). The lavas are highly magnetic and have a strong remanent magnetization which has been measured in the course of palaeomagnetic studies in northern England (Morris 1973 and Briden & Morris 1973). These authors reported a mean stable remanence direction of $D_r = 0^{o}$ and $I_r = -46^{o}$ (after correction for tectonic dip) total NRM intensities in the range 0.05 - 3.0 A/m and a Koeninsberger ratio of around unity (i.e. the ratio of the intesity of remanent magnetisation to the intensity of induced magnetisation in the Earth's field).

The magnetic anomaly has been modelled previously by Collar & Patrick (1978) along two short profiles adjacent to profile CD. These authors suggested three alternative models (Figure 7.30c) which explained the shape of the anomaly variously in terms of a wedge or block of lavas dipping steeply to the south or a sequence of lavas extending beneath the Carboniferous to the north. However, their models did not take account either of the longer wavelength magnetic anomalies across the Lake District or of the constraints imposed by the gravity data.

For the present interpretation, the in-situ intensity and direction of the total magnetization vector (i.e. the vector sum of the induced and remanent directions) has been calculated from the values reported by Briden & Morris (1973). The calculation was based on the assumptions that: (a) where the lavas lie nearest to the surface beneath profile CD their dip is around 70^{o} to the north as observed at



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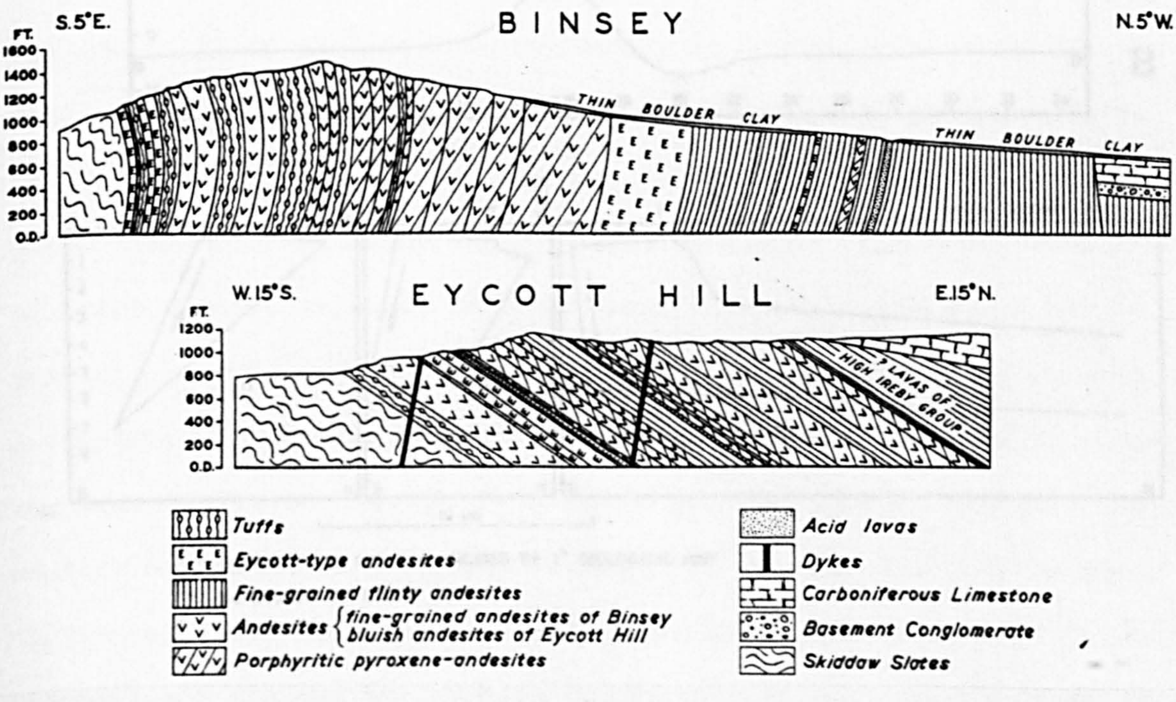

B

Figure 7.29 The Eycott lavas at Binsey (a) geological map, (b) sections across Binsey and Eycott Hill, from Eastwood et al. (1968)

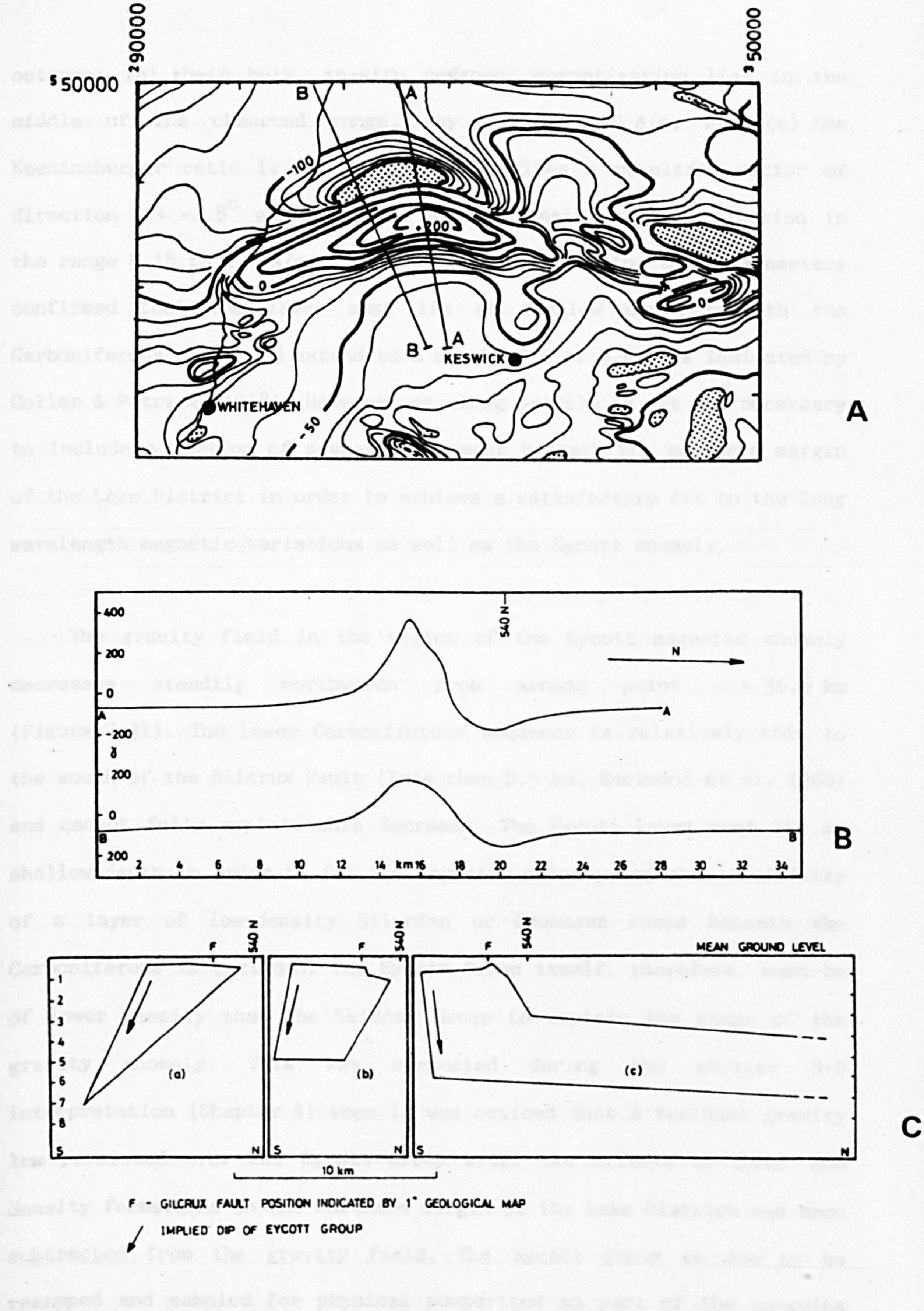

Figure 7.30 Interpretation of the form of the Eycott lavas near Binsey from Collar & Patrick (1978): (a) location of profiles A-A and B-B; (b) aeromagnetic anomalies along the profiles; (c) alternative interpretations.

outcrop; (b) their bulk, in-situ remanent magnetization lies in the middle of the observed range, say 0.1 to 1.0 A/m; and (c) the Koeninsberger ratio is around 1.0. This gives a resultant vector of direction D = -2.8° and I = 46.6° with intensity of magnetization in the range 0.18 to 1.8 A/m. Preliminary modelling using these parameters confirmed that the lavas must lie at shallow depth beneath the Carboniferous cover and extend to a depth of 4 or 5 Km, as indicated by Collar & Patrick (1978). However, as along profile AB, it was necessary to include a section of magnetic basement beneath the northern margin of the Lake District in order to achieve a satisfactory fit to the long wavelength magnetic variations as well as the Eycott anomaly.

The gravity field in the region of the Eycott magnetic anomaly decreases steadily northwards from around point x = 36.6 km (Figure 7.31). The Lower Carboniferous sequence is relatively thin to the south of the Gilcrux Fault (less than 0.5 km, Eastwood et al. 1968) and cannot fully explain this decrease. The Eycott lavas must lie at shallow depth in order to fit the magnetic anomaly, so the possibility of a layer of low-density Silurian or Devonian rocks beneath the Carboniferous is excluded. The Eycott Group itself, therefore, must be of lower density than the Skiddaw Group to explain the shape of the gravity anomaly. This was suspected during the earlier 3-D interpretation (Chapter 4) when it was noticed that a residual gravity low persisted over the Eycott Group after the effects of other low density formations on the northern margin of the Lake District had been subtracted from the gravity field. The Eycott Group is due to be remapped and sampled for physical properties as part of the on-going Lake District project but at the present time no density data are available. Models based on a range of density values have been tested and the most satisfactory fit to both the gravity and magnetic fields has been achieved by assuming that the Eycott lavas have an in-situ density of around 2.74 Mg/m^3 which is within the range measured for the Borrowdale Volcanic Group (see Section 5.5).

The final model (Figure 7.31) shows the Eycott lavas lying at shallow depth beneath the Lower Carboniferous between x = 34 km and the Gilcrux Fault (at x = 31 km on profile CD) where they are downthrown to the north by about 1 km. From this point northwards they thin rapidly towards the southern margin of the Carlisle Basin. The southern margin of the lavas is almost vertical, the preferred model suggesting a steep dip to the south (Figure 7.31). The overall form of their subcrop is compatible with a vertical or slightly overturned sequence where they are in contact with the Skiddaw Group (as indicated by the geological map, Eastwood et al. 1968), which flattens and thins to the north. It should be noted that the change in direction of the total magnetization vector, implied by a flattening of the tectonic dip of the Eycott volcanics northwards, has not been incorporated into the model. Trial models using a range of likely vector directions indicated that, given the other uncertainties, this factor was not critical to the main elements of the interpretation.

To the north of the Gilcrux Fault the geological map shows a thin Namurian sequence overlying lower Carboniferous rocks. Seismic data from the Carlisle Basin (Abbott pers. comm.) suggest that the Lower Carboniferous thickens rapidly, presumably across a faulted basin margin, to reach a depth of around 3 km by point x = 25 km on profile CD. It then thins gradually to the north to a depth of around 2 km beneath the general area of the Silloth borehole (which lies at

$x = 15.5$ km on profile CD). The same data show that the Permo-Triassic sequence thickens towards the Silloth borehole where its base lies at a depth of 1312 m. The Namurian sequence must thin towards the north as the Permo-Trias unconformably overlies the Lower Carboniferous at Silloth. The gravity gradient across this whole region (i.e. from the outcrop of the Skiddaw Group to the centre of the Carlisle Basin) is, however, strikingly uniform, and shows no major changes of gradient across the margins of the basin where the Lower Carboniferous must thicken from a few hundred metres to 3 km. This implies that the lowest Carboniferous rocks at depth are not of particularly low density and the gravity effect of Lower Carboniferous thickening is offset by a thinning of the Namurian, Eycott and possibly Silurian sequences towards the north.

The situation is similar in many respects to that along the northern margin of the Alston Block, where the Carboniferous sequence thickens rapidly along major growth faults (e.g. the Stublick - Ninety Fathom fault system) but has surprising little expression on the Bouguer anomaly map (Kimbell et al. 1988). The final model for profile CD (Figure 7.31) shows the Lower Carboniferous thickening rapidly, presumably across a major growth fault or series of faults, north of $x = 28$ km. The basal part of the Lower Carboniferous sequence has been assumed to have a density of around 2.70 Mg/m^3 which is based on that of the upper part of the Lower Border Group, measured from borehole logs in the Northumberland Trough (Kimbell et al. 1988). Between the Gilcrux Fault and the thickened Lower Carboniferous sequence, the model shows a formation of density 2.72 Mg/m^3, tentatively identified as a preserved section of Silurian rocks (SL? Figure 7.31). Rocks of density less than that of the Skiddaw Group are necessary in this location in

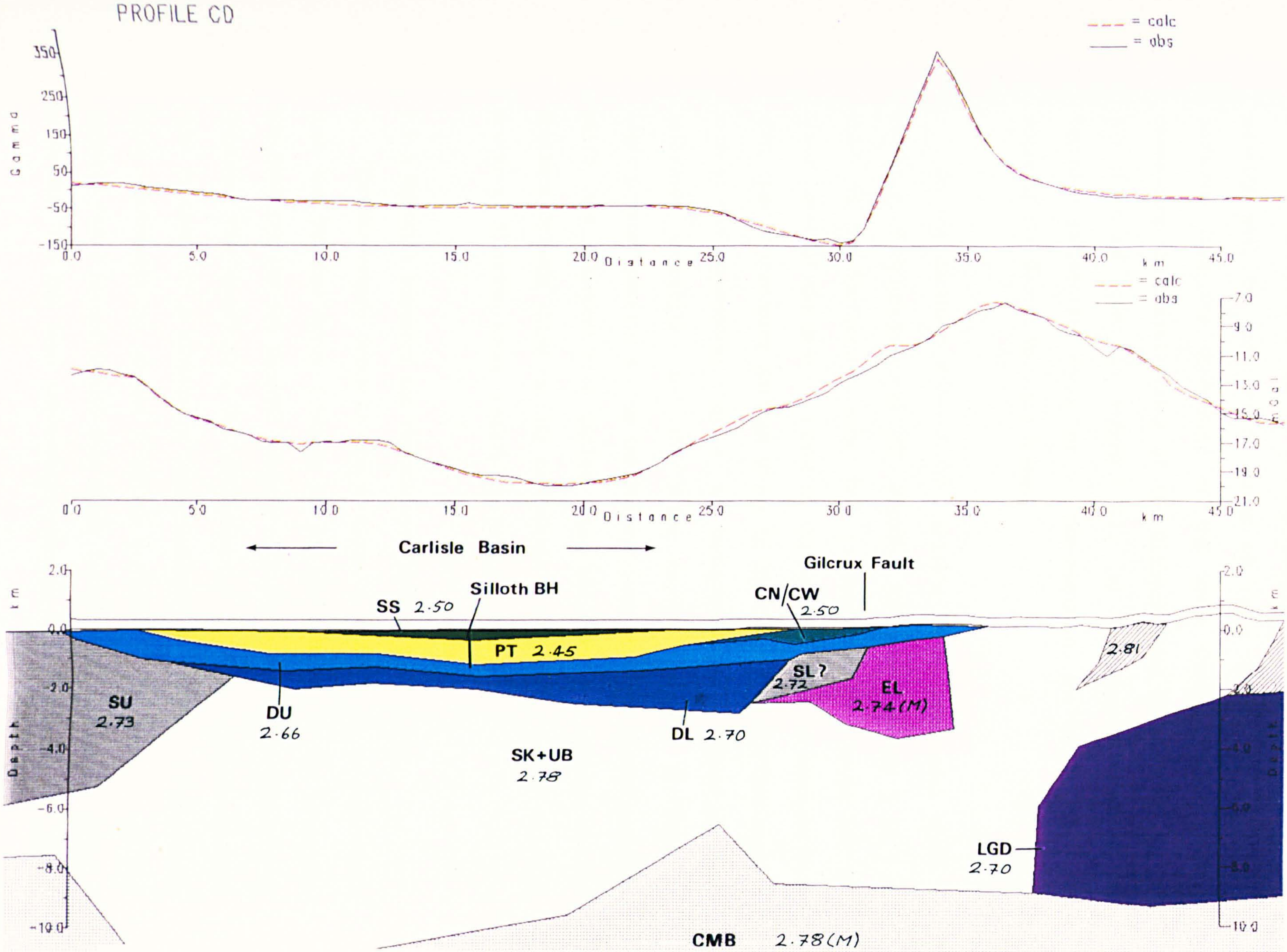

Figure 7.31 Northern part of CD.

order to achieve a fit to the gravity anomaly. However, the field could equally well be modelled in terms of (a) a thicker Carboniferous sequence (i.e the thickening of the Lower Carboniferous sequence commencing immediately north of the Gilcrux Fault rather than around x = 28 km as shown in Figure 7.31), (b) a preserved sequence of Devonian sedimentary rocks, or (c) non-magnetic, low density volcanic rocks of the Eycott Volcanic Group.

On the northern side of the Carlisle Basin, the model shows a sequence of Silurian rocks (SU, Figure 7.31) approximately 5 to 6 km thick in the Southern Uplands. This is necessary to account for the lower level of the gravity field in the Southern Uplands compared with that over outcropping Skiddaw Group in the Lake District but carries with it the assumptions that (a) the background gravity field has been estimated correctly, and (b) there is no contrast in mid- or lower-crustal density across the Solway line. If these assumptions are valid, the interpretation implies that the Silurian sequence in the Southern Uplands thins rapidly southwards and there is little room for preserved Silurian rocks beneath the Carlisle Basin.

7.9.3 Magnetic basement and the southern part of profile CD

The Windermere Group in the southern Lake District is less dense than the Skiddaw Group (Chapter 5) and gives rise to the prominent residual gravity low between about x = 77 and x = 96 km on profile CD (Figures 7.24 and 7.32). The preferred model (Figure 7.32) explains this in terms of a Windermere Group sequence up to 4 km thick, which thins southwards to around 1 km at x = 96 km. The maximum of the magnetic field occurs around this point (anomaly CM, Figure 6.17) and a reasonable fit has been achieved by assuming that magnetic 'basement' (as defined for profile AB, see Section 7.4) reaches to within 2 to 3 km of the surface at x = 96 km and lies just beneath the Windermere Group in the centre of the basin. However, the same dificulties apply to modelling the long wavelength components of the magnetic field along profile CD as have previously been discussed in relation to profiles AB and KL. The magnetic rocks must dip northwards beneath the batholith, then approach slightly nearer to the surface along the northern margin of the Lake Distict before deepening northwards beneath the Carlisle Basin.

The interpretation of profile CD (Figure 7.32) shows the top of the magnetic basement in contact with the base of the batholith which must, as a consequence, thin towards the south. Although this arrangement has been adopted as a reasonable interpretation for profiles AB, KL and CD, a variety of other explanations is possible. One such is shown in Figure 7.33. The longest wavelength magnetic anomalies are here explained in terms of magnetic basement buried at somewhat greater depth than on Figure 7.32, and the magnetic high at x = 95 km is interpreted as a separate, higher level body (properties for both bodies are as for the magnetic basement in Figure 7.32). Although the magnetic basement lies at greater depth it is still required to extend northwards beneath the batholith and to come nearer to the surface again beneath the northern margin of the Lake District. The main difference is that the gravity anomaly is explained in terms of a flat based batholith rather than one thinning to the south. The model also shows an absence of magnetic basement beneath the Carlisle Basin rather than northwards deepening basement. However, buried magnetic rocks must be present at depth beneath the Southern Uplands to account for the long wavelength magnetic highs observed there

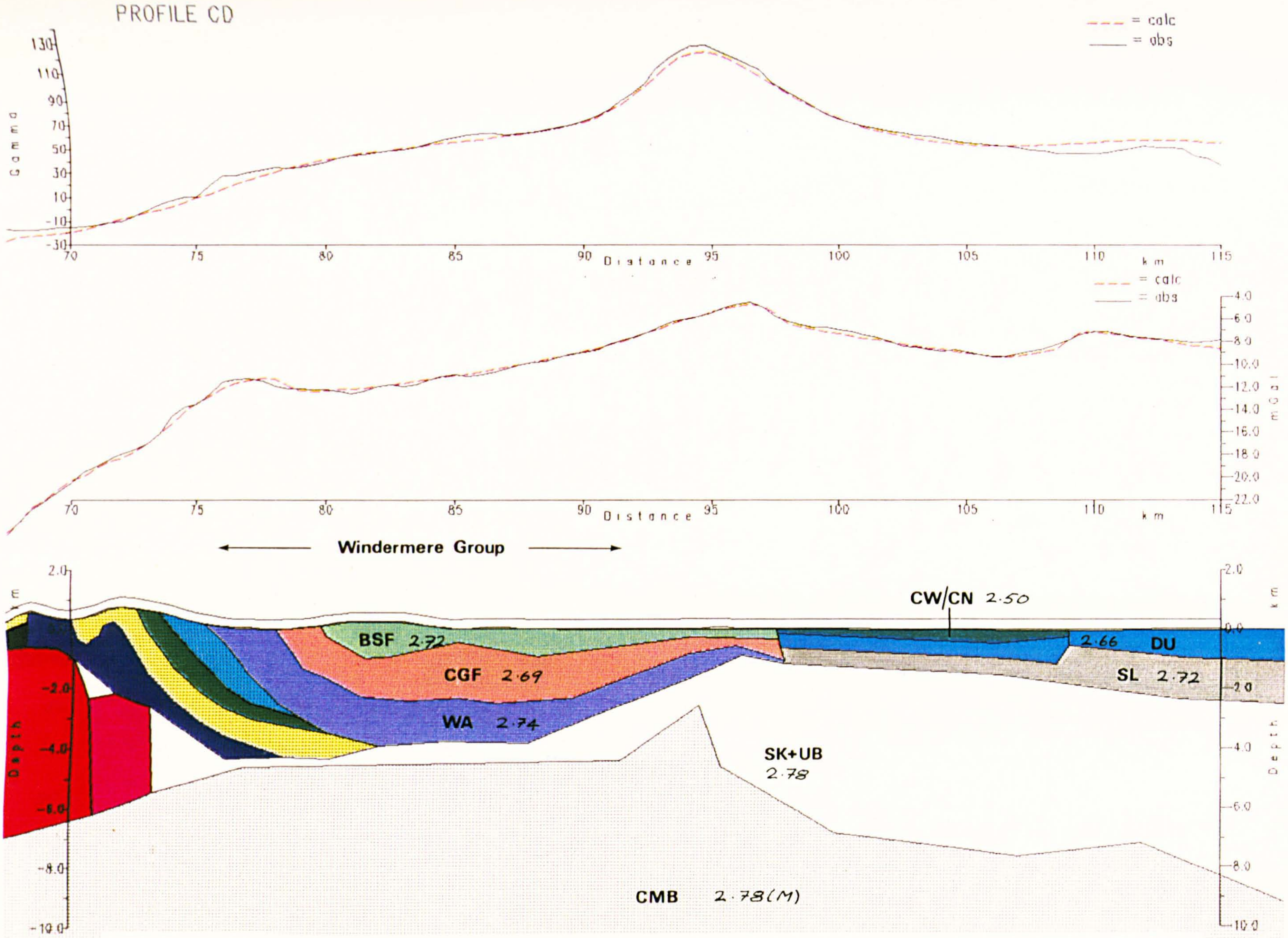

Figure 7.32 Southern part of CD.

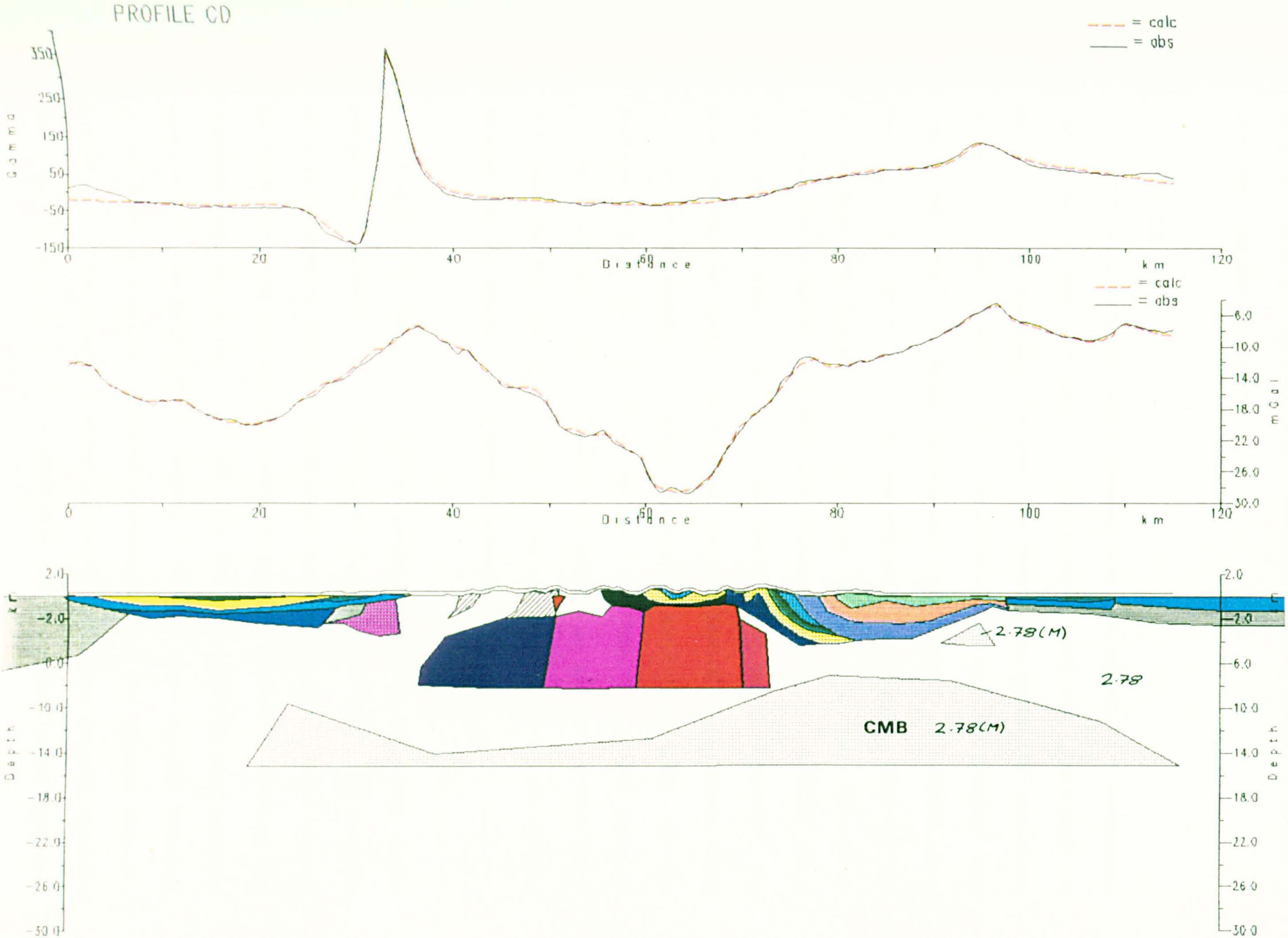

Figure 7.33 Alternative model for the magnetic basement beneath profile CD.

(Figure 7.31). The tectonic significance of these alternative models is discussed further in Chapter 8.

7.10 PROFILE YZ

Profile YZ (gravity only) crosses both the Scafell and Haweswater synclines of the Borrowdale Volcanic Group and was positioned to examine the relationship between the underlying batholith and these structures. Both synclines are characterized by residual gravity lows identified from the image processing (the Dunmail and Rydal lows respectively, Figure 6.17). The maximum negative anomaly (Figure 7.34) occurs over the Scafell Syncline (i.e. the Dunmail low). This lies between the Ullswater lineament and lineament 4 (see Figure 6.17) which intersect the profile at x = 11 km and x = 17.5 km respectively. The Rydal anomaly is visible as a broad residual low on the southern flank of the main anomaly, roughly coincident with the trace of the Haweswater Syncline (centred at around x = 20 km). The mapped trace of the Nan Bield Anticline intersects the profile at around x = 22.5 km. A distinct residual low also occurs on the northern flank of the anomaly between the Ullswater and Crummock lineaments.

Figure 7.34 shows an interpretation in terms of three major batholith components. As on profile CD (see Section 7.9), the presence of a major granite beneath the Scafell Syncline is unavoidable because it coincides with the maximum negative gravity anomaly. Following the arguments set out in Section 7.9.1 this has been modelled as a separate component of the batholith of density 2.66 Mg/m^3 (the Dunmail Granite) rather than as a simple eastwards continuation of the Eskdale Granite. A good fit to the observed anomalies is achieved with granite reaching to within about 1 km of the surface with the short wavelength anomalies being accounted for by variations within the overlying Borrowdale Volcanic sequence. Between the Ullswater and Crummock lineaments the interpretation shows an eastwards extension of the Buttermere Granite identified on previous profiles. North of the Crummock line the profile passes across the flank of the Skiddaw Granite where a two-dimensional modelling is invalid; body ULB (density = 2.70 Mg/m^3) represents the effects of the underlying batholith and the adjacent Skiddaw Granite. Slices of Skiddaw Group rocks of above average density (2.81 Mg/m^3, SKM on Figure 7.34) are included in the model in two places. The first is just to the north of the Crummock line as suggested from the interpretation of profile CD. The second is between the base of the Borrowdale Volcanic Group and the top of the Buttermere Granite near its contact with the Dunmail Granite. This helps to achieve a good fit to the steep gradient between about x = 10 and x = 14 km but the main evidence comes from profile GH farther east (see Section 7.12).

The interpretation shown in Figure 7.34 explains the Rydal residual gravity low, on the southern flank of the anomaly, in terms of a separate component of the batholith of density 2.68 Mg/m^3. The roof of the intrusion reaches to within about 1.5 km of the surface and approximately underlies the Haweswater Syncline. The Borrowdale Volcanic sequence is assumed to comprise a layer of Lower Volcanics of density 2.81 Mg/m^3 (group U, Figure 1.7) overlain by the Airy's Bridge Formation (density 2.70 Mg/m^3) and a sequence of Upper Volcanics of average density 2.77 Mg/m^3 (group P), the whole sequence thinning to the south beneath the Windermere Group.

Alternative interpretations for the southern half of the profile are shown in Figures 7.35 and 7.36. These attempt to explain the Rydal

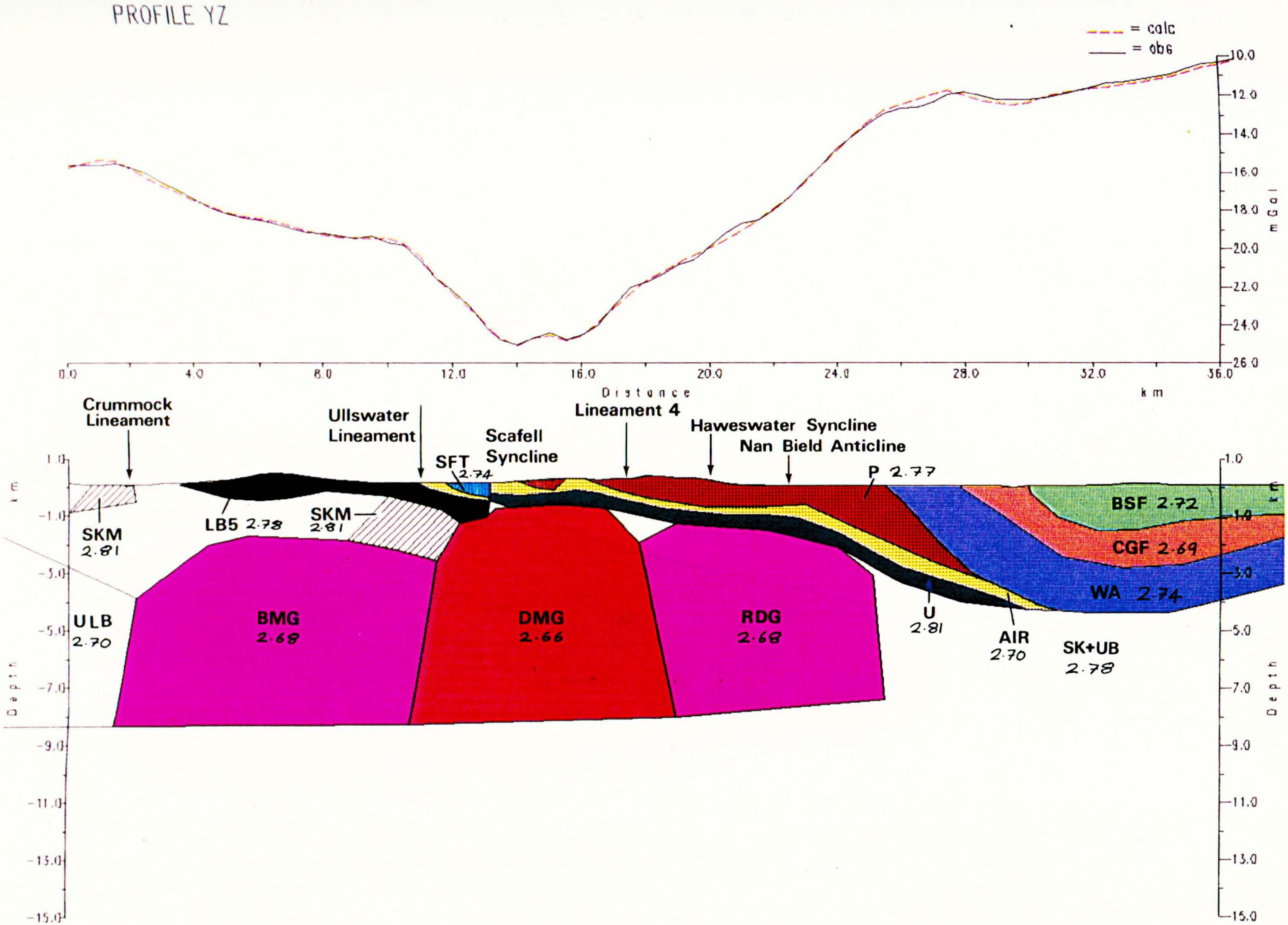

Figure 7.34 Interpretation along profile YZ.

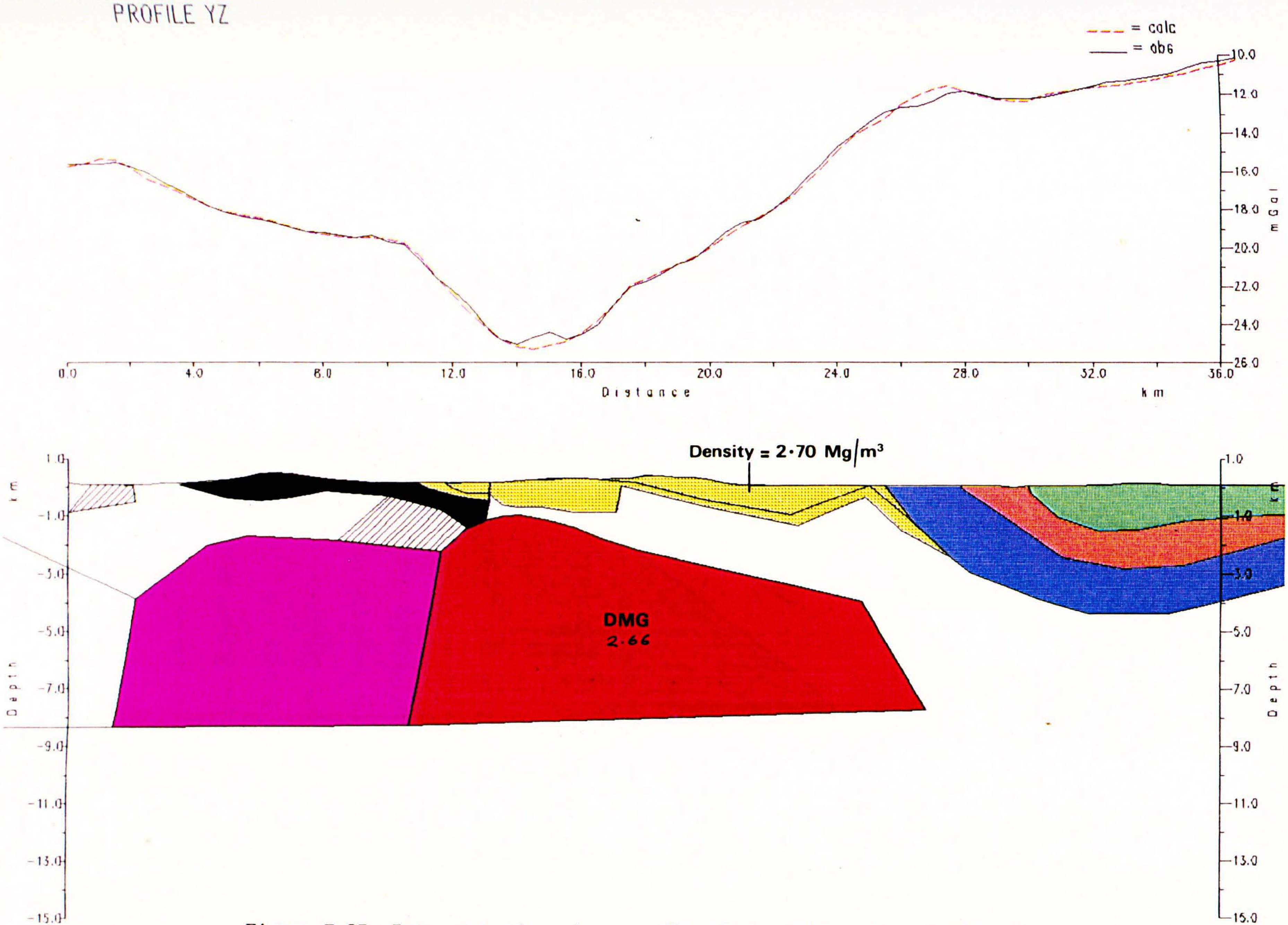

Figure 7.35 Interpretation along profile YZ assuming a low-density, Upper Borrowdale Volcanic sequence.

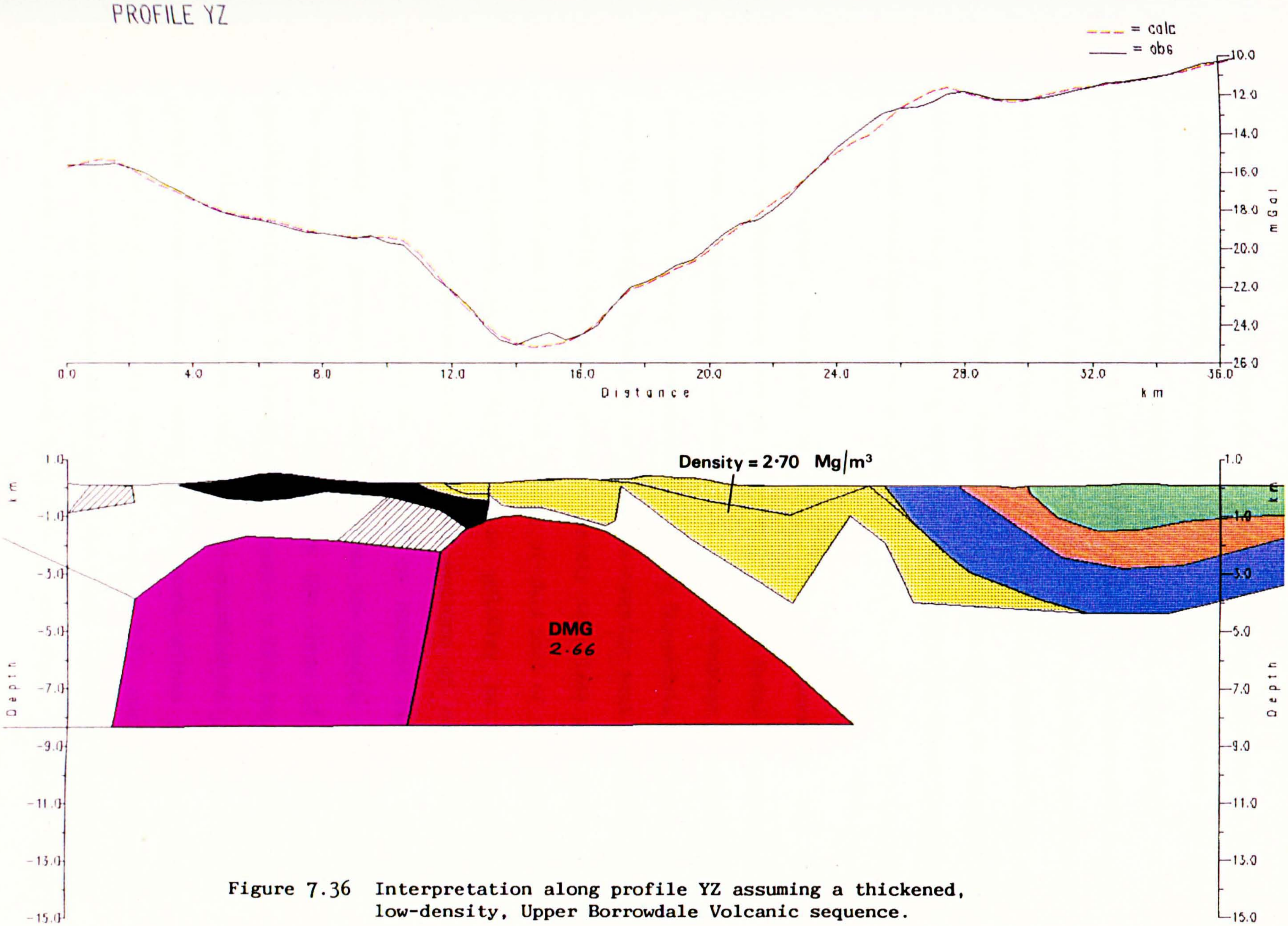

Figure 7.36 Interpretation along profile YZ assuming a thickened, low-density, Upper Borrowdale Volcanic sequence.

low in terms of a sequence of low-density Upper Borrowdale Volcanic rocks rather than an underlying granitic intrusion. In Figure 7.35 the (high-density) Lower Borrowdale sequence has been omitted and the entire Upper Borrowdale sequence given a density of 2.70 Mg/m^3 (i.e. equivalent to that of the Airy's Bridge Formation). A reasonable fit to the observed gravity anomaly is obtained but the underlying granite is still required in the form of shoulder extending southwards from the main Dunmail pluton (DMG). Figure 7.36 shows the effect of reducing the extent of this shoulder in which case a low-density, Upper Borrowdale sequence would need to be up to 4 km thick.

As always, variations on these models are possible, but they appear to demonstrate that an explanation of the Rydal low principally in terms of a thickened low-density volcanic sequence is unlikely for two reasons. Firstly, the sequence of Upper Borrowdale volcanics above the Airy's Bridge Formation in this area comprise mostly andesitic and basaltic tuffs (formation group P, mainly the Place Fell Tuffs, see Figures 1.3 and 1.7). The bulk density of this part of the sequence has been estimated as 2.77 Mg/m^3 and is unlikley to be as low as 2.70 Mg/m^3. A substantially thickened sequence of concealed Airy's Bridge ignimbrites would be required to account for the anomaly. Secondly, the greatest thickness of these low density volcanics would be required at around the point where the trace of the Nan Bield Anticline intersects the profile (at around $x = 22.5$ km). This point is most significant because the thickest accumulation of low-density Airy's Bridge Formation would be expected within the Haweswater Syncline (c.f. the Ulpha Syncline, Section 7.8) and an attenuated sequence would be expected across the Nan Bield Anticline (D. Millward, pers. comm.). It would seem most likely, therefore, that the Rydal residual gravity low is at least partly due to the presence of a substantial, and possibly separate component of the batholith, here referred to as the Rydal Granite (RDG, Figure 7.34), which approximately underlies the trace of the Haweswater Syncline.

7.11 PROFILE EF

Profile EF was sited to cross the centre of the Carlisle Basin gravity low, the eastern part of the batholith (i.e. through the Skiddaw Granite and Threlkeld Microgranite) and the Windermere magnetic high in the southern Lake District. The final interpretation is shown in Figures 7.37 and 7.38.

The profile passes close to the eastern end of the batholith where 2.5D modelling is not entirely appropriate. This applies in particular to the section north of the Ullswater lineament where the concealed (and adjacent) parts of the batholith have been represented by a body of density 2.68 Mg/m^3 (ULB on Figures 7.37 and 7.38). The Skiddaw Granite is modelled as a steep-sided pluton on the northern margin of the batholith as suggested by previous 2-D and 3-D modelling (Bott 1974 and Chapter 4 respectively).

The Crummock line intersects the profile at x = 49 km (Figure 7.38). The Threlkeld Microgranite crops out to the south of the line but the gravity anomaly associated with the intrusion clearly straddles the line. The most satisfactory fit was given by a laccolithic intrusion extending northwards from the outcrop at very shallow depth beneath the Skiddaw Group rocks. A slice of Skiddaw Group of above average density (SKM) has been included between the Threlkeld microgranite and the Skiddaw Granite. This helps the fit to the steep gravity gradients in the area and is in line with suggestions from other profiles to the west that there is a density contrast between Skiddaw Group rocks to the north and south of the Crummock line.

Profile EF intersects the Ullswater Lineament at around x = 58 km. A concealed slice of Skiddaw Group rocks of above average density (SKM, Figure 7.38) is included in the model on the northern side of the lineament, mainly on evidence from profile GH to the east (see Section 7.12). However, short wavelength gravity anomalies in this area are not particularly well defined by the regional gravity data and have not been modelled in detail.

To the south of the Ullswater Lineament the profile crosses the eastern end of the Dunmail and Rydal residual gravity lows (see Figure 6.17). These coincide with the Scafell and Haweswater synclines respectively and were modelled in terms of two underlying (separate) components of the batholith on profile YZ. However, on profile EF the Dunmail low is considerably narrower and the concealed batholith is modelled as a single body of density 2.68 Mg/m^3.This represents mainly the Rydal component of the batholith but possibly includes the eastern end of the Dunmail component along its northern edge (RDG+DMG Figure 7.38). As on profile YZ, it seems unlikely that the upper Borrowdale Volcanic sequence within the Haweswater Syncline is sufficiently thick or of sufficiently low density to explain the gravity anomaly without recourse to a substantial underlying component of the batholith. The preferred model (Figure 7.38) shows a relatively flat-lying granite roof at a depth of around 2 km beneath the Haweswater and Scafell synclines. South of the Nan Bield Anticline (at around x = 69.5 km) the granite roof and the overlying volcanics dip more steeply to the south.

To the south of the batholith the Borrowdale Volcanic sequence is assumed to thin beneath the thickening Windermere Group which itself thins southwards from around x = 80 km. The main magnetic high in the southern Lake District (WI, Figure 6.17) coincides with the thickest development of the Windermere Group and has been modelled as magnetic basement (as specified for previous profiles) reaching to within about 5 km of the surface. This basement must dip northwards beneath the batholith, as on other profiles to the west, but possibly at a deeper level. The magnetic rocks reach slightly nearer to the surface again along the northern margin of the Lake District before dipping steeply beneath the Carlisle Basin.

To the north of the Skiddaw Granite, both the gravity and magnetic fields are particularly complex and it is difficult to fit both simultaneously. Within the Carlisle Basin, seismic evidence (Abbott pers. comm.) suggests that the Lower Carboniferous sequence thickens rapidly to a depth of over 4 km at around x = 21 km and then thins northwards. The base of the Permo-Triassic sequence reaches its maximum depth of around 1.5 km at x = 18 km. Initial models based on the seismic data overestimated the magnitude of the negative gravity anomaly over the Carlisle Basin, even taking into account that the density of the lower part of the Lower Carboniferous sequence probably increases to around 2.70 Mg/m^3 (Kimbell et al. 1988). However, profile EF traverses the western flank of the large positive magnetic anomaly in the Carlisle area (feature CL on Figure 6.17). A reasonable fit to both gravity and magnetic fields is achieved if this is modelled as body of density 2.95 Mg/m^3 and susceptibility 0.03 SI (CBI on Figure 7.37), possibly representing a mafic intrusion within the upper crust (see Section 7.12 for further discussion of this feature). As on profiles farther west there is little room for low density Silurian rocks beneath the Carlisle Basin but the Silurian sequence thickens northwards into the Southern Uplands.

The part of the profile between the Skiddaw Granite and the southern margin of the Carlisle Basin is also problematic. The steep gravity gradient on the northern side of the Skiddaw Granite decreases over the outcrop of the Eycott Volcanic Group. The same effect was noted on profile CD and presumably indicates that the bulk density of the Eycott group is lower than that of the Skiddaw Group. A positive magnetic anomaly is clearly associated with the Eycott lavas but its amplitude is significantly less than on profile CD. Examinination of the magnetic field in this area (Figures 2.7, 6.6b and 6.14) shows that the Eycott anomaly is interrupted in the region of the Skiddaw Granite in a manner which suggests that the intrusion of the granite may have partially destroyed the magnetization of the Eycott lavas (possibly due to hydrothermal alteration of the magnetite?). The model shown in Figure 7.37 is based on this hypothesis and gives a reasonable fit to both gravity and magnetic fields. The magnetization of the lavas is set at 0.25 A/m (c.f. 1.2 A/m for profile CD) and their density is set at 2.74 Mg/m^3. The model implies a steeply dipping sequence of Eycott lavas on the northern margin of the Lake District, flattening and thinning to the north.

The Lower Carboniferous sequence is relatively thin to the north of the Eycott Group outcrop (Eastwood et al. 1968)) but the top of the magnetic lavas must dip northwards to fit the shape of the magnetic anomaly. However, rocks of lower density than the Skiddaw Group must be present in order to fit the gravity field. The preferred model shows a solution in terms of a concealed Silurian sequence (SL, Figure 7.37) beneath the Carboniferous, although a sequence of non-magnetic Eycott lavas would give an equally good fit. The small magnetic anomaly centred at around x = 28 km has been modelled as a separate sequence of magnetic lavas but the body could equally well represent a slice of magnetic basement rocks. Note, however, that the profile crosses this anomaly at a very oblique angle so the model is not reliable at this point.

7.12 PROFILE GH

Profile GH was sited principally to cross the Shap and Haweswater granites and the eastern inliers of the Eycott Group (at Eycott Hill and Greystoke, Figure 1.1). It also extends northwards to cross the centre of the Carlisle magnetic anomaly (feature CL, Figure 6.17) and southwards to the Wensleydale Granite. The final interpretation is shown in Figure 7.39 and details of the central part of the profile are given in Figure 7.40. Two points should be noted regarding the position of the profile. Firstly, it runs at an oblique angle to the strike of the broad magnetic anomaly which extends from the Askrigg Block to the southern Lake District (features AB and WI, Figure 6.17) and is therefore not suitable for studying the form of the deep magnetic basement. A layer representing the basement has been included (CMB Figure 7.39) to provide a background for modelling the shorter wavelength magnetic anomalies but its form, especially in the southern Lake District, should not be taken as definitive. The second point is that, north of the Haweswater pluton, the profile runs adjacent to the

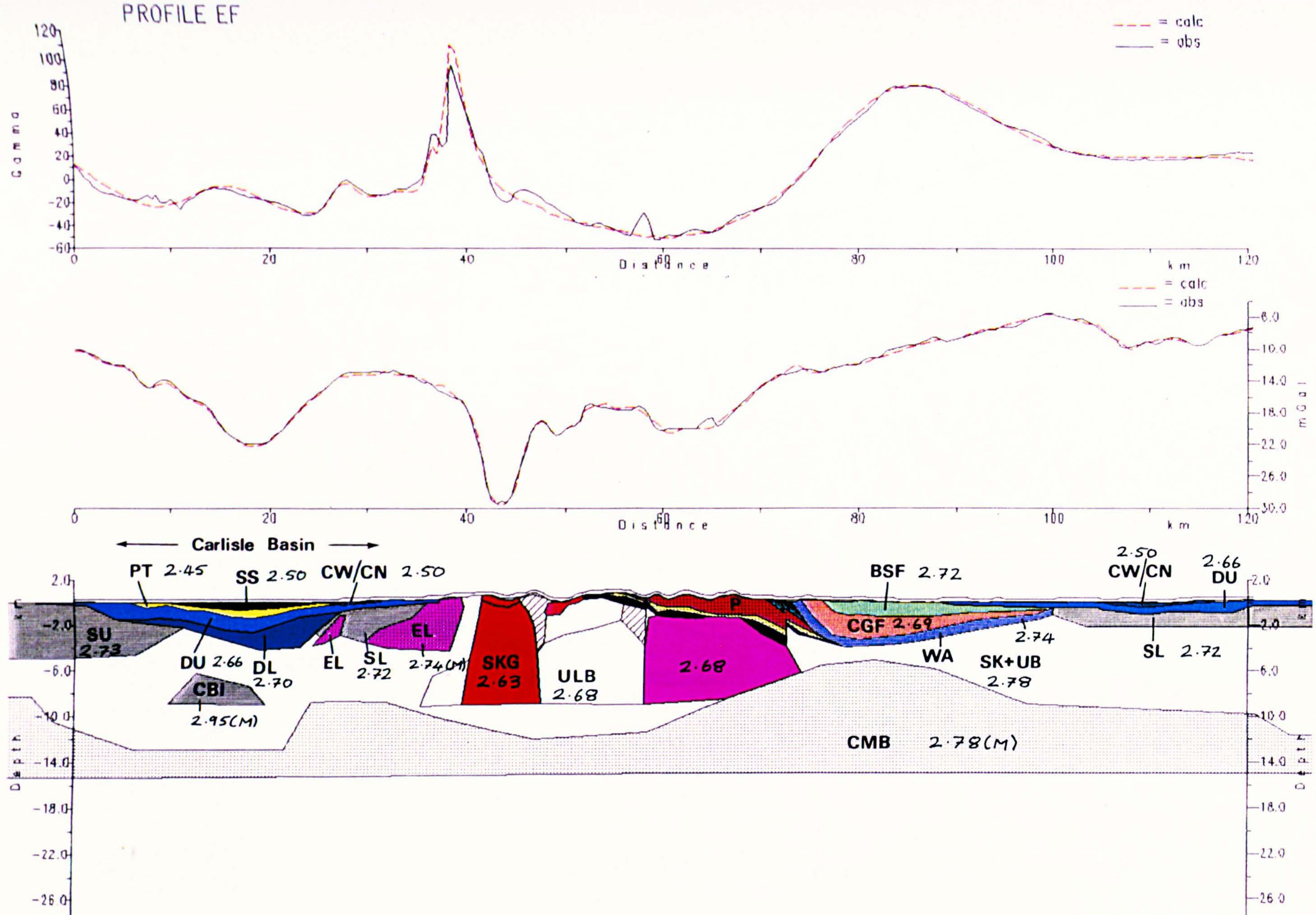

Figure 7.37 Interpretation along profile EF.

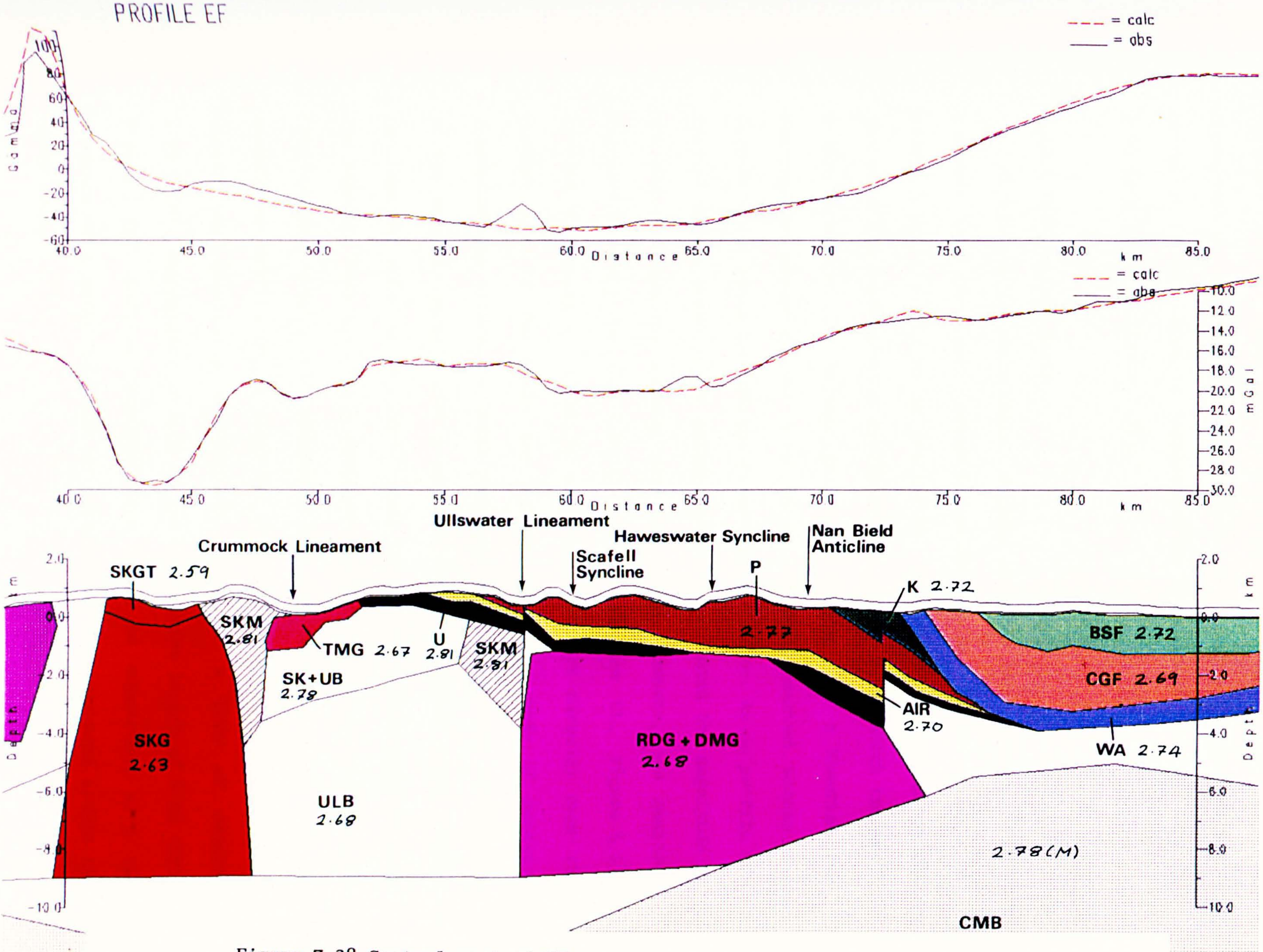

Figure 7.38 Central part of EF.

Skiddaw Granite where two dimensional modelling of the gravity anomalies is not entirely appropriate. The effect of the adjacent batholith in this area is represented by a concealed body of density 2.68 Mg/m^3 (ULB on Figure 7.39).

7.12.1 The Carlisle Basin

Within the Carlisle Basin, seismic evidence (Abbott pers. comm.) suggests that the Lower Carboniferous succession reaches a depth of around 5 km at x = 12 km on profile GH. This point corresponds to the centre of the Carboniferous synclinal axis in the basin which trends in a NNE direction. The seismic data also suggest that a Namurian and Westphalian sequence over 1 km thick may be preserved within the Carboniferous basin beneath the Permo-Triassic cover. As on profile EF, initial models based on the seismic data overestimated the magnitude of the negative gravity anomaly over the basin. However, the positive magnetic anomaly in the Carlisle Basin (feature CL, Figure 6.17, centred at around x = 12 km on profile GH) occurs directly over the deepest part of the basin and must be due to a body of positive susceptibility within the underlying basement. The spatial correlation of the magnetic anomaly with a relative positive gravity ridge between two lows was noted in Section 6.7 (see Figure 6.17). This suggests that the magnetic body also has a positive density contrast with respect to the basement which could compensate for the mismatch to the gravity anomaly on profile GH. A good fit to both the gravity and magnetic fields was eventually achieved in terms of a body of density 2.95 Mg/m^3, susceptibility 0.03 SI and half strike length of 8 km (CBI, Figure 7.39). Such an interpretation would be consistent with the presence of a mafic intrusion of subcircular form emplaced within the upper crust.

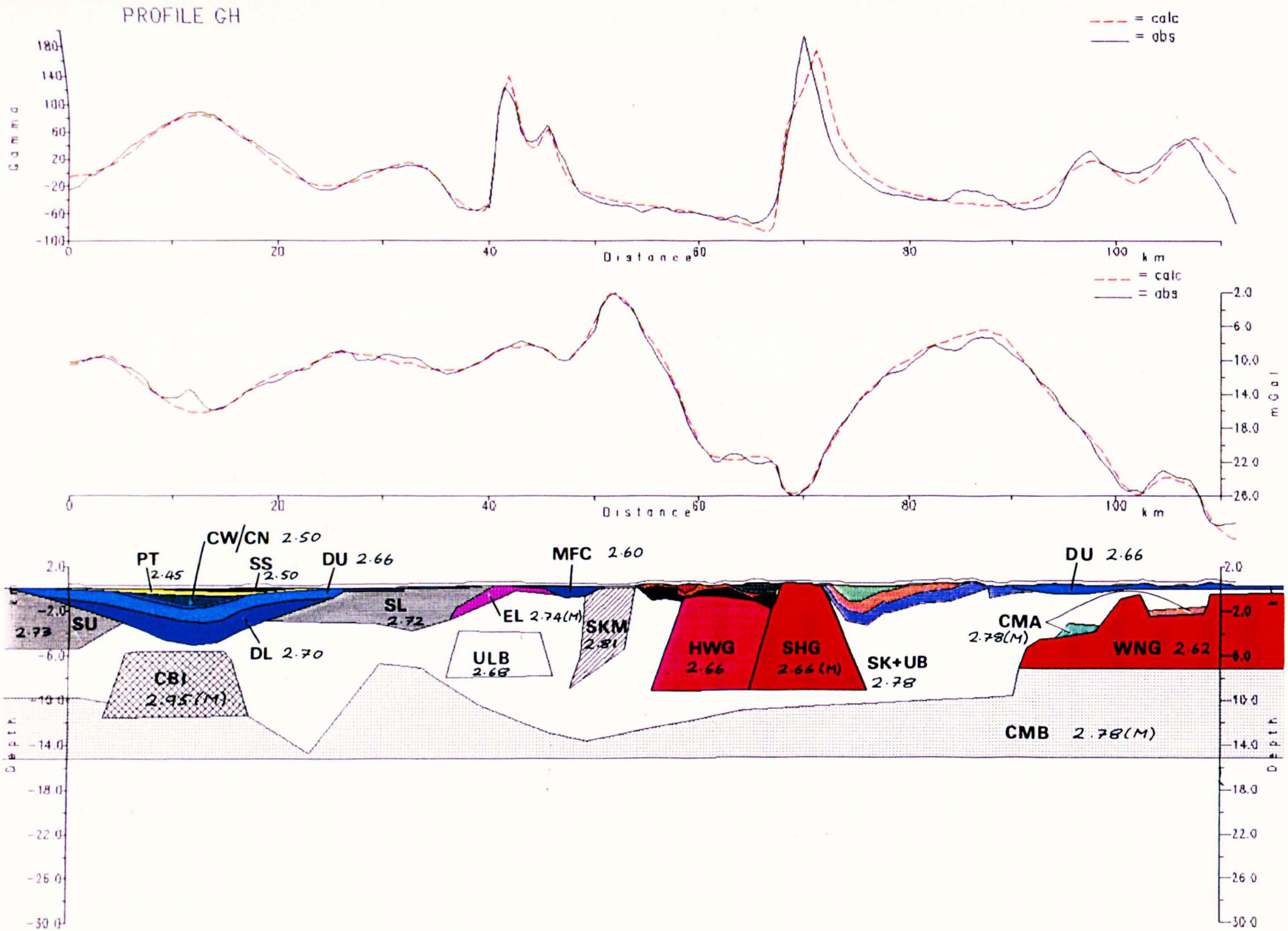

Figure 7.39 Interpretation along profile GH.

7.12.2 The Shap and Haweswater granites

The form of the batholith in the Shap/Haweswater area follows closely that defined by previous interpretations (Bott 1974, Locke & Brown 1978 and Chapter 4). The Shap Granite is a steep-sided intrusion which crops out between x = 68 and x = 70 km on profile GH. The roof region clearly extends southwards beneath a thin cover to around x = 71.5 km, which corresponds to the southern edge of the metamorphic aureole. The Haweswater Complex comprises sporadic outcrops, mostly of dolerite, totalling 2.6 km^2 over an area of about 19 km^2 (Nutt 1979). On profile GH these outcrops occur mostly between x = 60 to x = 63 km. Density measurements on a representative suite of rock types from the complex (Table 4.1) give values within the range measured for the Borrowdale Volcanic Group and it is clear that the Haweswater Complex must be underlain by a granitic intrusion. As in previous interpretations, a density of 2.66 Mg/m^3 has been adopted for the Haweswater pluton (i.e. the same value as measured for the Shap Granite). The resulting model shows a relatively flat-lying granite roof at a depth of around 1 km beneath the Haweswater Complex (Figure 7.40) which could be interpreted in terms of either a northwards extension of the (early Devonian) Shap Granite or a separate intrusion.

The magnetic anomaly over the Shap Granite is slightly more difficult to explain. The aeromagnetic map (Figure 2.7) shows a prominent positive anomaly of about 250 nT approximately over the granite outcrop (around x = 70 km on profile GH). Locke & Brown (1978) carried out detailed ground magnetic and gravity surveys over the Shap Granite and demonstrated that the aeromagnetic anomaly resolved into two separate magnetic highs on the ground, to the southwest and northeast of the outcrop respectively. They suspected a country rock source marginal to the intrusion and made magnetic susceptibility measurements on samples of the granite and adjacent Borrowdale Volcanic Group lavas (Table 7.2 below).

Table 7.2 Magnetic susceptibility values for the Shap Granite and adjacent lavas from Locke & Brown (1978).

Sample	**Induced magnetization (x 10**-5 emu/g)**	**Equiv susceptibility (1) (x 10**-3 SI)**
Shap Granite	18.5	12.9 (2)
Volcanics (1m from contact)	114.7	83
Volcanics (20m from contact)	25.4	18.3
Volcanics (magnetically quiet areas)	4.0	2.8

NOTES

(1) Equivalent susceptibility in SI units calculated assuming a density of 2.66 Mg/m**3 for the Shap Granite and 2.76 Mg/m**3 for lavas.

(2) c.f susceptibility 8.5 x 10**-3 SI measured from borehole samples (Chapter 3).

On the basis of these measurements, Locke & Brown (1978) concluded that the granite alone could not be responsible for the magnetic anomaly because models based on their gravity interpretation gave a calculated response of only 50 nT compared with over 250 nT measured by the aeromagnetic survey. Instead they explained the anomaly solely in terms of a magnetized skin of Borrowdale volcanics adjacent to the granite and proposed a body approximately 0.75 km high and 0.5 to 1 km wide for the anomaly on the southwest margin of the granite. However, whilst it is clear from their ground survey and magnetization data that magnetized lavas must be responsible for the local magnetic highs on the margins of the granite, the present interpretation is at variance with that given by Locke & Brown (1978) on two counts.

Firstly, their contention that the granite alone is insufficient to explain the aeromagnetic anomaly cannot be verified. In fact, models based on their measured magnetization value of 0.0129 SI give a calculated anomaly of over 300 nT and the value of 0.0085 SI measured from the borehole core (see Table 7.2 above) is probably more representative of the intrusion as a whole. Secondly, models based on magnetized lavas alone (bodies BS, Figure 7.41) do not explain the longer wavelength components of the aeromagnetic anomaly. Profile GH runs between the magnetic peaks resolved by Locke & Brown (1978) on the southwest and northeast sides of the granite and is, therefore, not perfectly placed to examine the magnetic field in detail. However, the model shown in Figure 7.40 suggests that the anomaly is best explained in terms of the combined effects of a moderately magnetic granite and marginal, highly magnetic lavas.

The recognition that the Shap Granite itself is at least partly responsible for the magnetic anomaly over the outcrop invites comparison with the granitic intrusion beneath the Haweswater Complex. The magnetic field is relatively flat across this area and the underlying intrusion is assumed to be non-magnetic in the model shown in Figure 7.40 (body HWG). Figure 7.42 shows the effect of assuming a susceptibilty of 0.0085 SI for the Haweswater pluton (i.e. the same as for the Shap Granite). It is clear from the resulting mismatch between the observed and calculated magnetic fields that the Haweswater pluton must be essentially non-magnetic. This in turn implies that it is not a simple northwards extension of the Shap Granite but is a distinct and separate intrusion.

7.12.3 The Ullswater Lineament and the Eycott Group

The northern margin of the Haweswater Granite is characterized by a steep gravity gradient and there is a relative positive gravity anomaly centred at around x = 52 km (Figure 7.40). This positive anomaly occurs over the Ullswater inlier of the Skiddaw Group and is in turn flanked by a further residual gravity low on its northern side which corresponds to the outcrop of the Devonian Mell Fell Conglomerate (Capewell 1955). The Ullswater gravity high shows up as a prominent feature on the gravity maps and images (e.g. Figures 6.6a) and is difficult to model without assuming the presence of a high-density body beneath the Ullswater inlier. This anomaly was noted by Collar (1981) who, whilst recognizing that there is no corresponding positive magnetic anomaly (see Figure 7.40), thought an underlying mafic intrusion the most likely explanation.

The present study, however, has led to the recognition of the Ullswater Lineament which intersects profile GH at x = 54 km. The lineament stretches from the Ullswater inlier westwards across the batholith and, possibly, eastwards to the Cross Fell inlier (see Figure 6.17). For most of its extent the Ullswater lineament is characterized by gravity highs to the north and gravity lows to the south. Within the central Lake District this is partly due to the fact that the lineament marks the northern limb of the Scafell Syncline and the northern margin of the Eskdale/Dunmail components of the batholith. However, this would also be compatible with an interpretation of the lineament as the contact between tracts of slightly differing density within the Skiddaw Group. The interpretation shown in Figure 7.40 is based on this possibility and explains the positive anomaly in terms of a slice of Skiddaw Group rocks of above average density (body SKM). This could represent a tract of predominantly mudstone lithologies to the north of the Ullswater lineament in a similar arrangement to that suggested for the Crummock lineament.

The geological re-mapping programme has not yet reached the Ullswater area and there are, as yet, no detailed density measurements to support this interpretation. Existing information (A.H. Cooper, pers. comm.), indicates that the Skiddaw Group sequence at the surface in the Ullswater inlier comprises mainly soft mudstones which are unlikely to be of particularly high density. The top of the high-density rocks may, therefore, be concealed beneath these, rather than reaching the surface as shown in Figure 7.42. Overall, the presence of concealed high density Skiddaw Group mudstones also helps to fit steep gravity gradients across the Ullswater lineament on the other profiles to the west of GH, and this explanation is considered more likely than a mafic intrusion beneath the Ullswater inlier. The interpretation is also compatible with the concept of a slice of high-density mudstones dipping eastwards beneath the Vale of Eden and being cut out from below by the batholith to the west of the Ullswater inlier.

The Crummock lineament intersects profile GH at around $x = 45.5$ km. This point lies at the southern limit of the magnetic anomaly associated with the Eycott lavas which crop out between $x = 40$ and $x = 42$ km in the Greystoke inlier and about 3 km along strike to the WSW in the Eycott inlier (see Figure 7.1). Collar (1981)

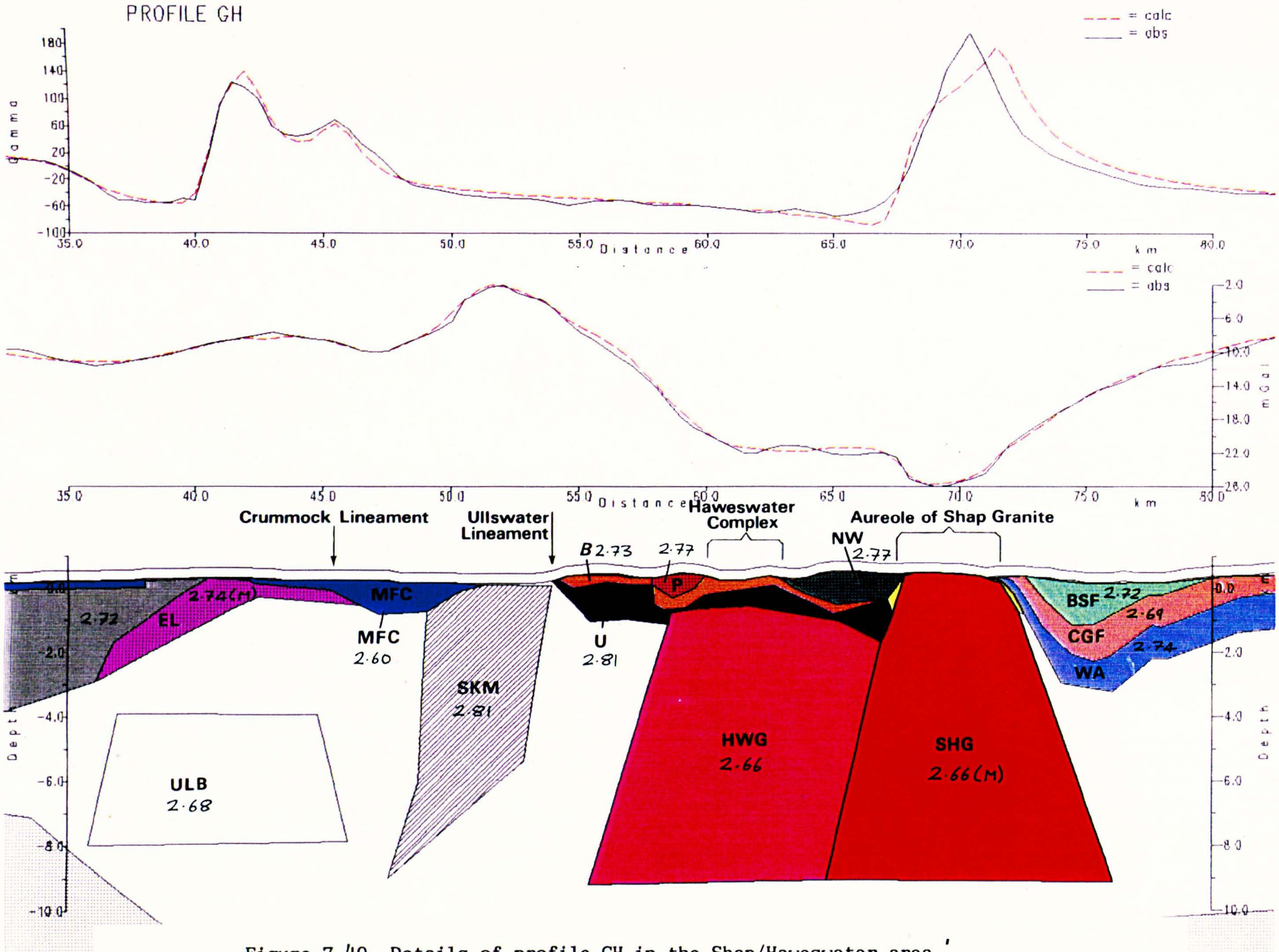

Figure 7.40 Details of profile GH in the Shap/Haweswater area.

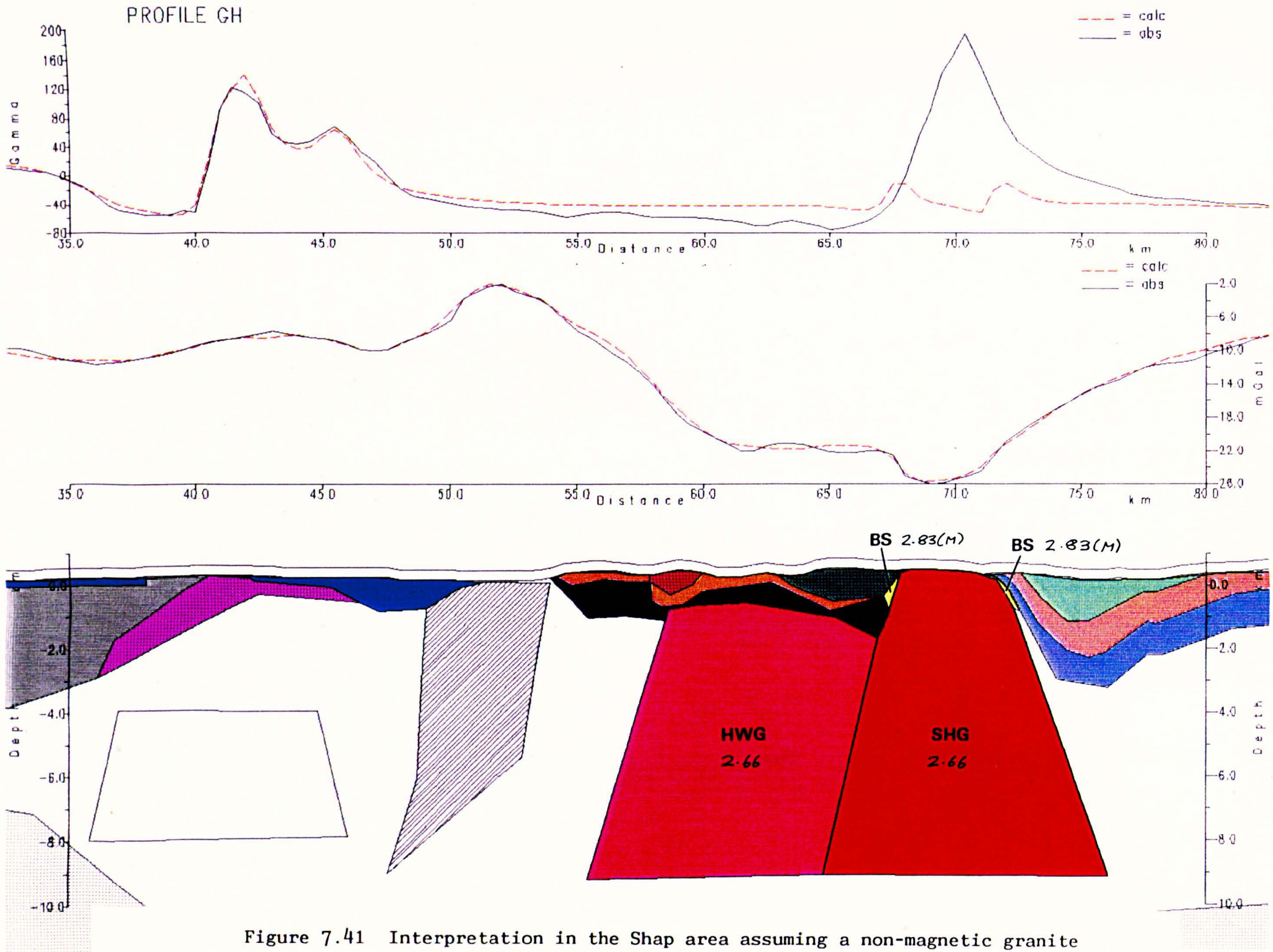

Figure 7.41 Interpretation in the Shap area assuming a non-magnetic granite and magnetic lavas around the intrusion

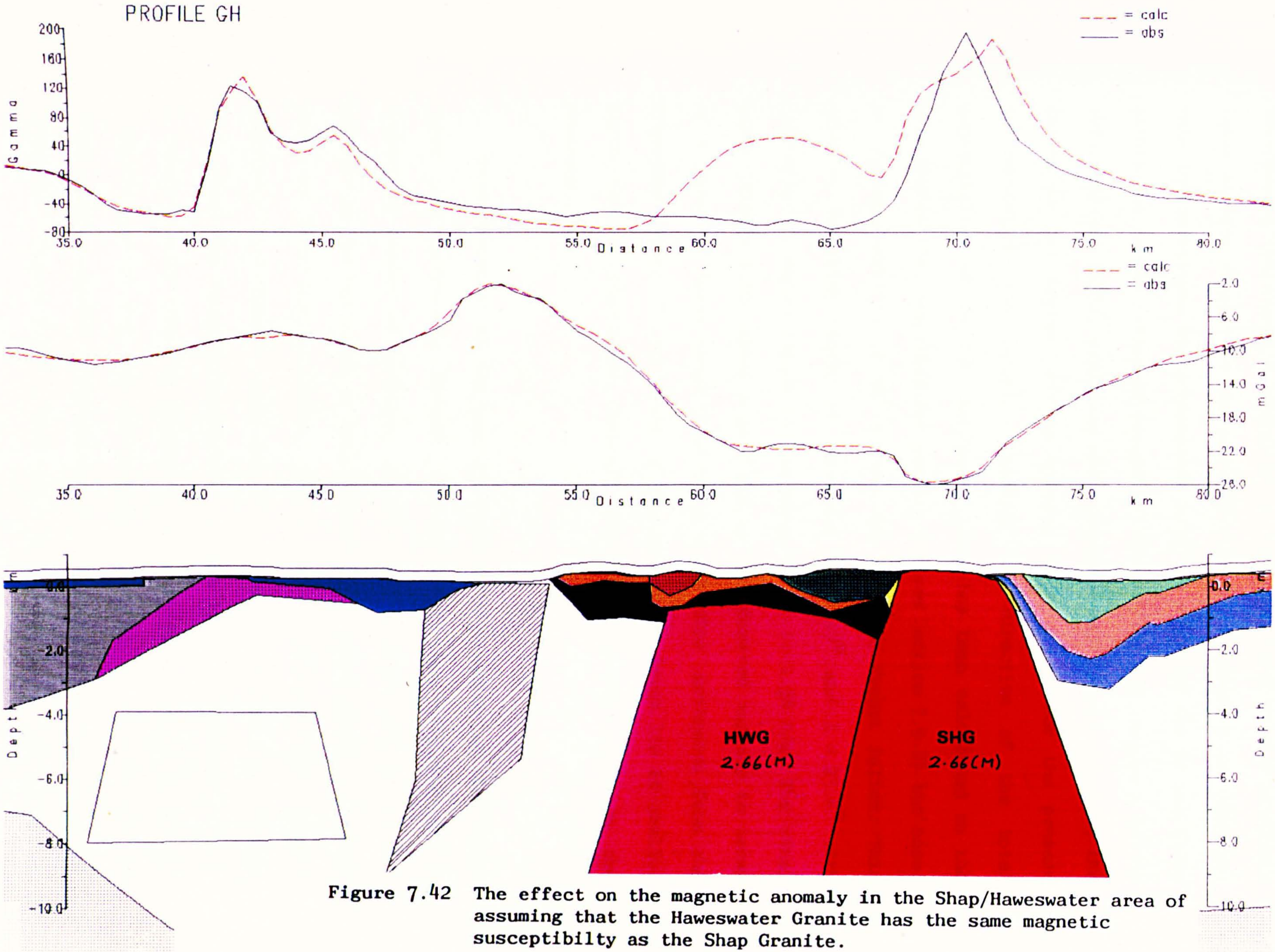

Figure 7.42 The effect on the magnetic anomaly in the Shap/Haweswater area of assuming that the Haweswater Granite has the same magnetic susceptibilty as the Shap Granite.

interpreted the magnetic anomalies in terms of thick sheets of Eycott lavas dipping steeply to the south to a depth of around 5 km. However, this interpretation is incompatible with the observed dip of the lavas within the Eycott inlier of around 38^{o} towards the ENE (Briden & Morris 1973). Collar (1981) explained this inconsistency by assuming that the inlier is not typical of the subcrop as a whole. For the present interpretation the in-situ intensity and direction of the total magnetization vector for the Eycott lavas has been calculated in the same way as that described for profile CD (see Section 7.9.2) but based on the observed dip of 38^{o} to the ENE from the Eycott inlier. This gives a resultant vector of direction $D = 13.7^{o}$ and $I = 23.4^{o}$ with intensity of magnetization in the range 0.134 to 1.34 A/m. The final model (Figure 7.40) gives a good fit to the observed anomaly in terms of a layer of lavas about 1 km thick which dips northwards from the Greystoke inlier. To the south of the inlier the lavas lie at shallow depth beneath the Lower Carboniferous cover as far south as the Crummock line.

Interpretation of the gravity field in the region of the Eycott lavas, and northwards towards the margin of the Carlisle Basin, presents a number of problems. As mentioned above, the profile runs adjacent to the batholith in this region and this is represented in the model by body ULB at depth. However, the gravity field remains relatively flat between here and the southern edge of the Carlisle Basin where the Lower Carboniferous sequence is relatively thin. Rocks of lower density than the Skiddaw Group must be present beneath the Carboniferous to fit to the gravity field in this area and the interpretation assumes a concealed Silurian sequence around 4 km thick (body SL, Figure 7.39). This is compatible with the proposed interpretation of the Eycott Group in that younger rocks must lie above the northwards dipping lavas to the north of the Greystoke inlier. The possible presence of a concealed Silurian sequence on the northern margin of the Lake District is also supported by the existence of the Drygill Shales, of Caradoc age, in a small outlier on the northern margin of the Carrock Fell Complex (Eastwood et al. 1968).

7.13 PROFILE IJ

Profile IJ runs east-west across the Lake District batholith (i.e along the Caledonian strike) from the Irish Sea to the Weardale Granite. It was positioned to check the interpretations from the cross-strike profiles and to examine the western amd eastern margins of the batholith. The direction of the profile is not appropriate for modelling the deep magnetic basement and modelling was, therefore, based on the gravity data only. The final model (Figure 7.43) corroborates the general form of the batholith as defined by the cross-strike profiles. Thus, in the central Lake District, a reasonable fit to the observed gravity field has been achieved in terms of concealed batholith components of density 2.66 Mg/m^3 and 2.68 Mg/m^3 representing the Dunmail (DMG) and Rydal (RDG) granites respectively. In general though, the shape of the batholith is less constrained, and the effect of structures within the Borrowdale Volcanic Group are more difficult to model than is the case for the cross-strike profiles (see Table 7.1 for the values of half-width used in the model).

The form of the East Irish Sea Basin, which lies to the west of the Lake District, has been defined from seismic data by Jackson et al. (1987) and a map of the depth to the top of the pre-Permian surface has been published by BGS (Smith 1985). These show a complex structure

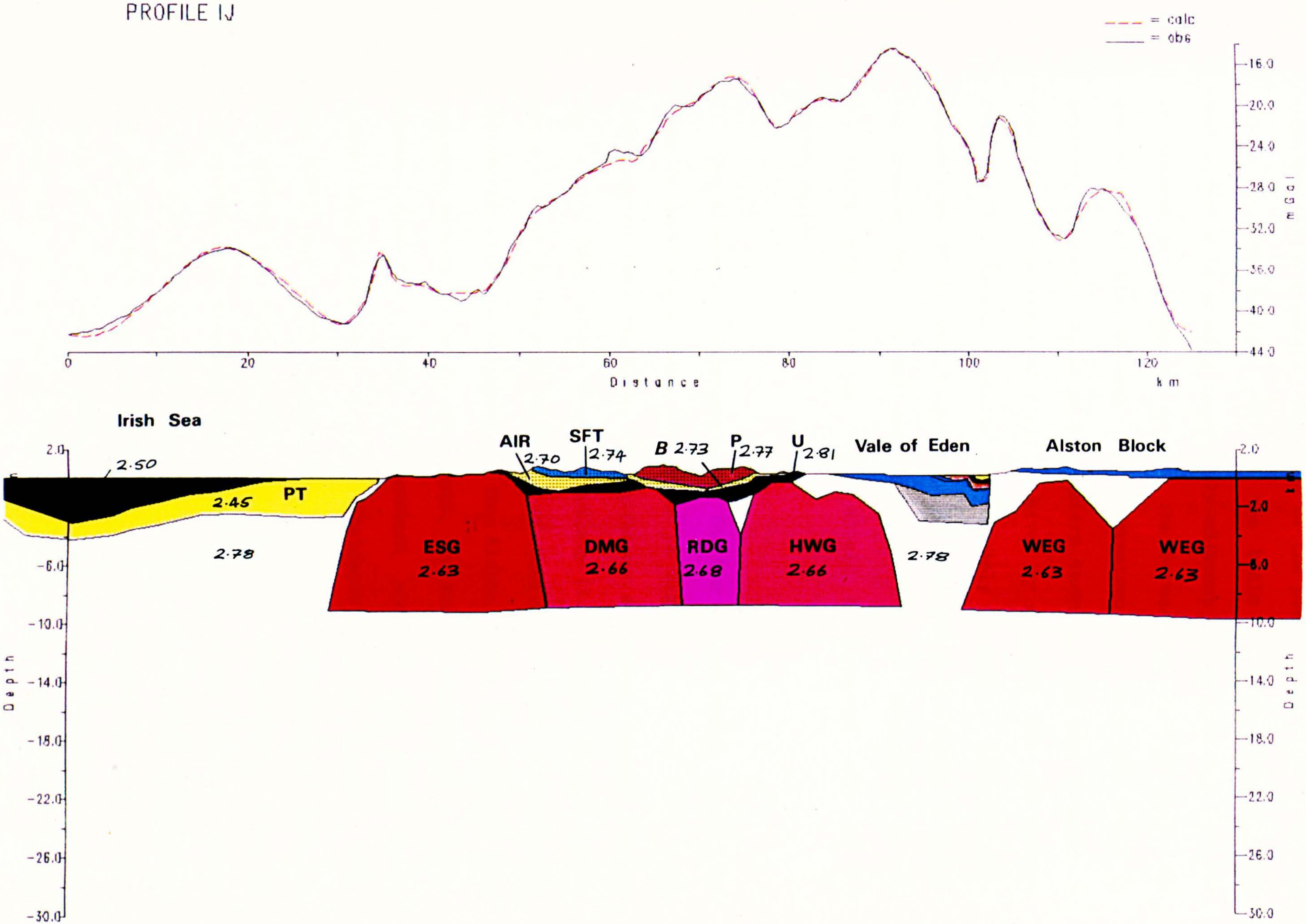

Figure 7.43 Interpretation along profile IJ.

superimposed on a general deepening of the pre-Permian floor to around 4-5 km in the central part of the basin (the Keys Basin). The Carboniferous is missing immediately adjacent to the Lake District but is assumed to be present beneath the Permo-Trias farther west. The present interpretation uses this information as a starting point to explain the gravity field on the western margin of the Lake District. A good fit to the observed field is given by assuming that the western flank of the Eskdale Granite dips steeply beneath a Permo-Triassic sequence which thickens to around 3 km immediately off-shore. However, the gravity field is not well defined off-shore, especially in the near-shore area, and the model should be regarded only as an approximation.

Two alternative interpretations for the eastern margin of the Lake District and Vale of Eden are given in Figures 7.44 and 7.45. Bott (1974) noted that the Lower Carboniferous succession dipping towards the Vale of Eden between Shap and Appleby (i.e. roughly between x = 85 and x = 95 km along profile IJ) is of thin Block type, in structural continuity with the sequence on the Alston Block. In contrast, the sequence around 15 km to the south, in the Ravenstonedale - Kirby Stephen district, forms the western end of the thick Lower Carboniferous sequence in the Stainmore Trough (Turner 1927, Bott 1967). Bott (1974) recognized that the exact position of the hinge line between the thick and thin successions is indeterminate across the Vale of Eden but concluded that at least part of the negative anomaly must be due to a basement feature such as a granite ridge linking the Shap and Weardale granites (profile IJ roughly follows the line of this ridge). He noted that the gravity effect of the ridge was masked in the central part of the Vale of Eden by the negative anomaly due to the

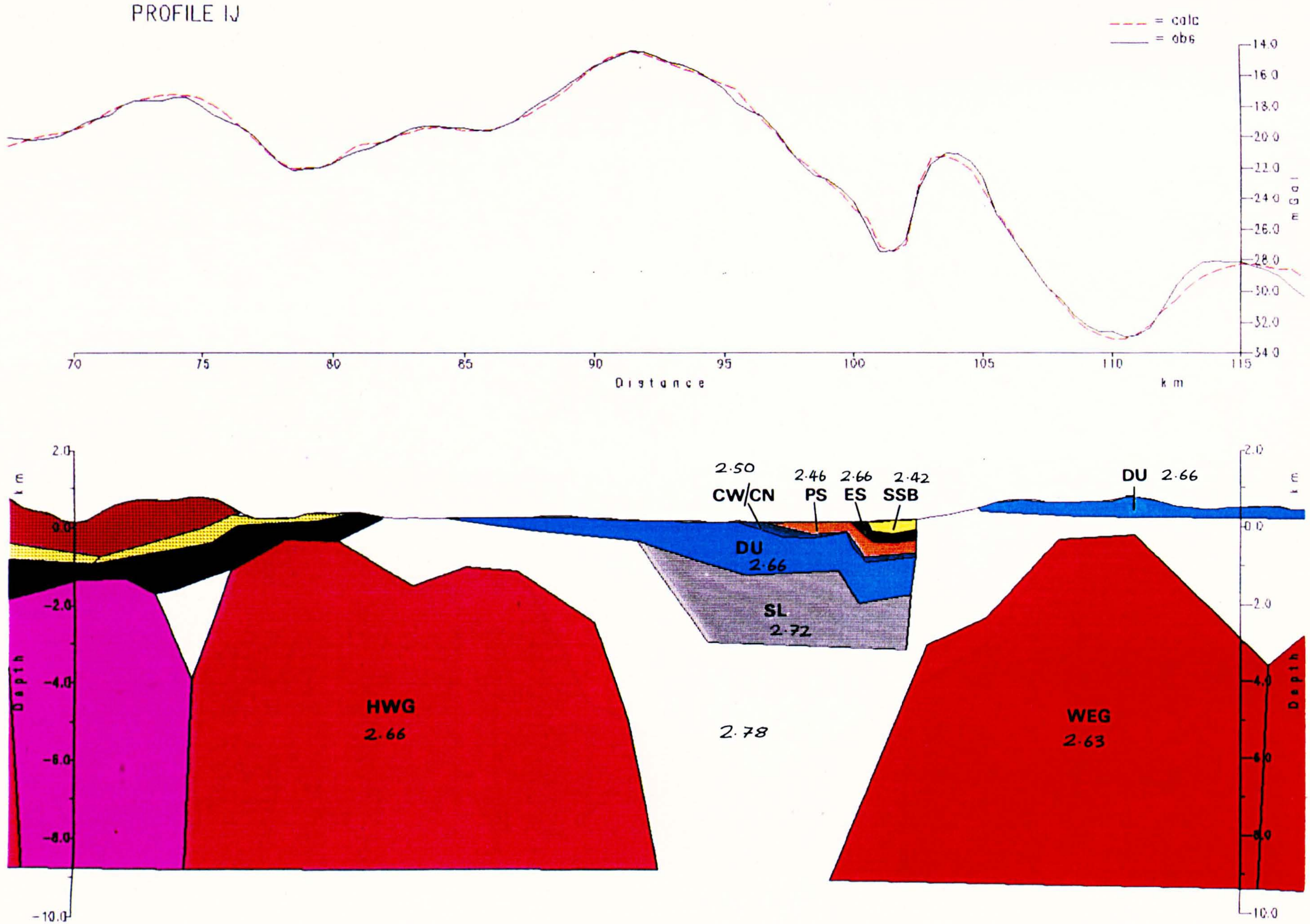

Figure 7.44 Details of profile IJ across the Vale of Eden.

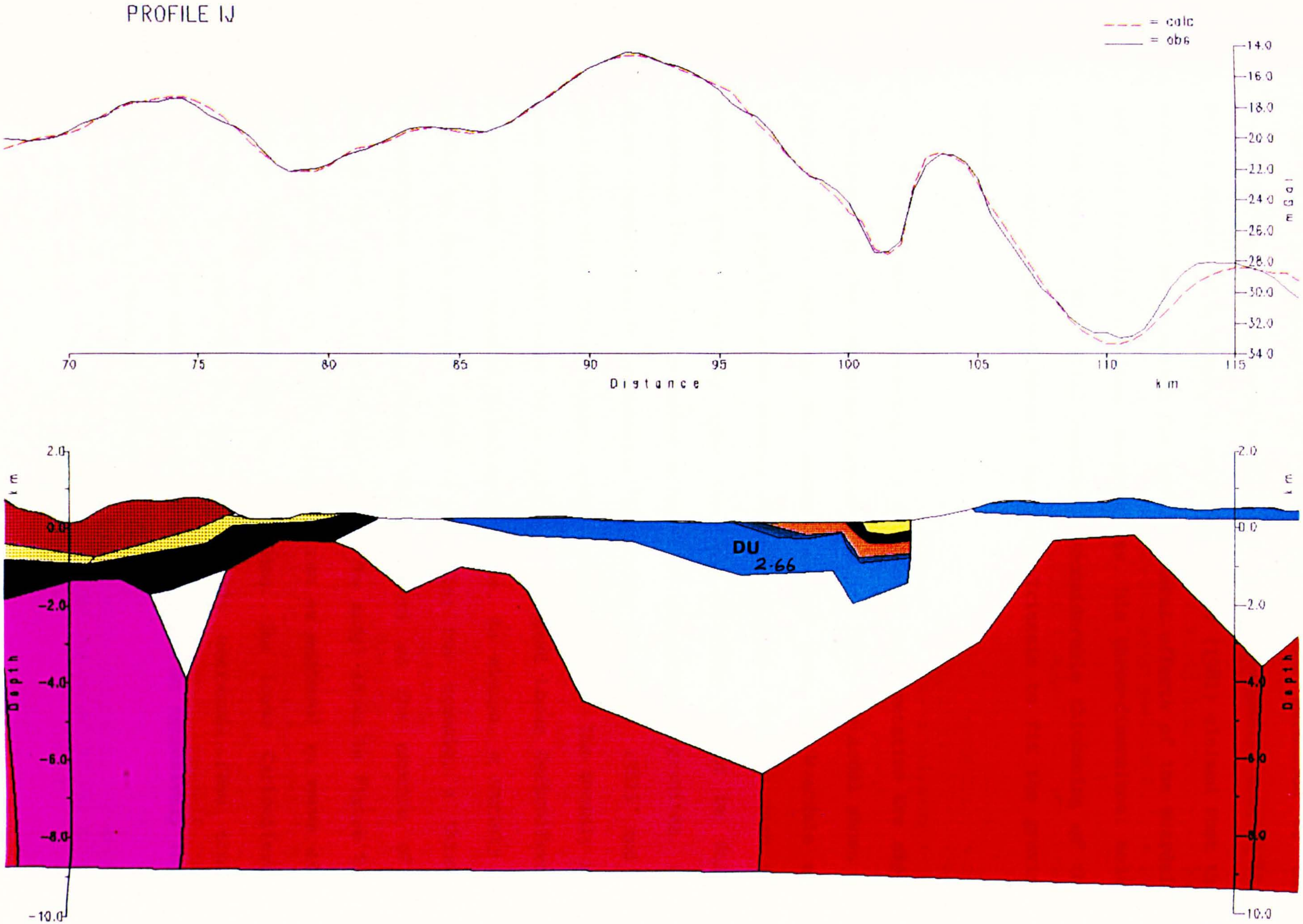

Figure 7.45 Alternative model across the Vale of Eden assuming a deep-seated connection between the Weardale and Lake District batholiths.

Permo-Triassic succession but cited the obvious extension of the Haweswater anomaly (referred to by him as the Shap anomaly) towards the ENE in support of a ridge. In contrast, Collar (1981) claimed that the anomaly could be accounted for by the lateral effects of the Weardale and Lake District granites. Nevertheless, his three-dimensional model of the Vale of Eden still required a considerable thickening of the Carboniferous sequence beneath the Permo-Triassic to fit the gravity anomaly.

The problems of arriving at a definitive interpretation are amply illustrated by the comparing Figures 7.44 and 7.45. The model shown in Figure 7.44 is based on the assumption that both the Weardale and Haweswater granites have steeply dipping margins. In this case the negative gravity anomaly over the Vale of Eden cannot be fully accounted for by the combined effects of the adjacent granites, the known Permo-Triassic succession (Arthurton & Wadge 1981) and a relatively thin (500 m) Lower Carboniferous sequence. The anomaly has been explained in terms of a slightly thickened Lower Carboniferous layer above a concealed Silurian sequence. As always, a variety of models on this general theme is possible; for example, a thicker Carboniferous sequence (Upper and/or Lower) at the expense of a thinner, or absent Silurian succession. The model shown in Figure 7.45 demonstrates that an equally good fit can be achieved in terms of a granite ridge beneath the Vale of Eden. The Lower Carboniferous sequence is required to thicken slightly westwards from around $x = 92$ km but the concealed Silurian sequence (or an excessively thick Carboniferous succession) is not required.

KEY TO MODELS IN CHAPTER 7

Permo-Triassic

Stanwix Shales	= SS	St Bees & Kirklinton Sst	= SSB
St Bees Shales	= SBS	Eden Shales	= ES
Penrith Sandstone	= PS	Permo-Triassic undivided	= PT

Carboniferous/Devonian

Westphalian	= CW	Namurian	= CN
Dinantian (U Lid - M Bord)	= DU	Dinantian (Lower Border Gp)	= DL
Mell Fell Conglomerate	= MFC		

Silurian

Kirby Moor Formation	= KMF	Bannisdale Slate Formation	= BSF
Coniston Grit Formation	= CGF	Wenlock to Ashgill strata	= WA
Undivided (Lake District)	= SL	Undivided (Southern Uplands)	= SU

Borrowdale Volcanic Group

Upper BVG - Composite formations = G, K, NW, P, SFT, DF, UL, B, AIR.
Lower BVG - Composite formations = U, LB5, LB4, LB3, LB2, LB1.
Altered BVG around Shap Granite = BS
Buried magnetic BVG? on prof KL = LB

Eycott and Skiddaw Groups

Eycott Volcanic Group	= EL	Skiddaw Group undivided	= SK
Siltstone/mudstone lithologies	= SKM		

Exposed Lake District Granites

Eskdale Granite	= ESG	Wasdale Granite	= WSG
Eskdale Granodiorite	= EGD	Ennerdale Granophyre	= ENG
Ennerdale Microdiorite	= EM	Threlkeld Microgranite	= TMG
Skiddaw Granite - main	= SKG	Skiddaw Granite - top	= SKGT
Shap Granite	= SHG		

Postulated concealed components of the Batholith

Crummock Granite	= CWG	Haweswater Granite	= HWG
Coniston Granite	= CNG	Loweswater Granodiorite	= LGD
Dunmail Granite	= DMG	Buttermere Granite	= BMG
Rydal Granite	= RDG	Ulpha Granite	= ULG

Undivided batholith, concealed and/or adjacent (off profile) = ULB

Other Granites

Wensleydale Granite	= WNG	Weardale Granite	= WEG
Criffel Porphyritic Granodiorite	= CRG	Criffel Main Granodiorite	= CMG

Concealed Basement

Undifferentiated basement	= UB	Carlisle mafic intrusion	= CBI
Magnetic L. Pal. (Askrigg Block)	= CMA	Concealed magnetic basement	= CMB
Magnetic sheet (profile AB)	= CMS		

Density values (in Mg/m^3) are shown on the models where possible. A positive magnetization contrast with respect to background is indicated by (M) after the density (see Table 7.1 for values).

CHAPTER 8

LAKE DISTRICT STRUCTURE - DISCUSSION AND CONCLUSIONS

8.1 FORM OF THE BATHOLITH

The image analysis and detailed modelling described in Chapters 6 and 7 provide a basis for updating the simple 3-D model of the Lake District batholith shown in Figure 4.9. A revised model showing both the postulated subsurface form and possible component parts of the batholith is shown in Figure 8.1 (the contours were derived mainly from the 2.5-D interpretations with guidance from the earlier 3-D interpretation). Solid contours show depth to the roof of the deep-seated batholith components (down to 6 km) and the thick dashed lines show the extent of shallow (high level) intrusions. Thin dashed contours give an indication of the possible form of the southern margin of the batholith assuming substantially thickened Borrowdale Volcanic sequences within the Haweswater and Ulpha synclines. A schematic cross-section of the Lake District, based on the 2.5-D models, is shown in Figure 8.2.

A total of six separate granitic intrusions is recognized at outcrop and there is evidence from the gravity modelling for a further eight concealed intrusions, some as deep-seated components of the batholith and others as high-level granitic intrusions. The form of the batholith shown in Figure 8.1 is based on the maximum number of separate components which can be inferred from the gravity data (a possible total of 14). The evidence for some of these is better than for others and in a number of cases alternative interpretations are possible. The components are listed below with a summary of supporting evidence where appropriate.

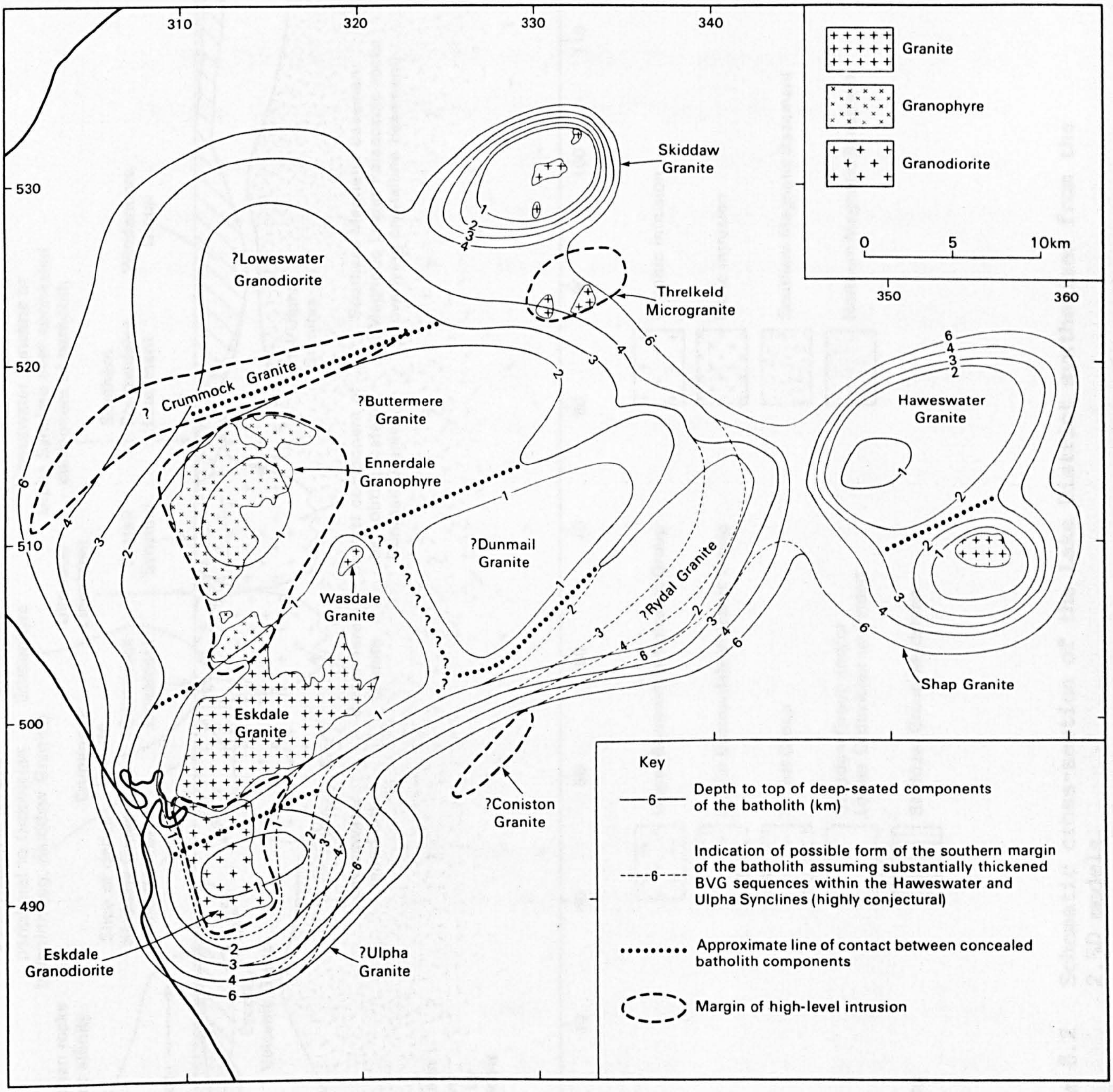

Figure 8.1 The 3-D form of the Lake District batholith and its various components synthesized from the 2.5D gravity/magnetic models and the earlier, simplified 3-D interpretation of Lee (1986).

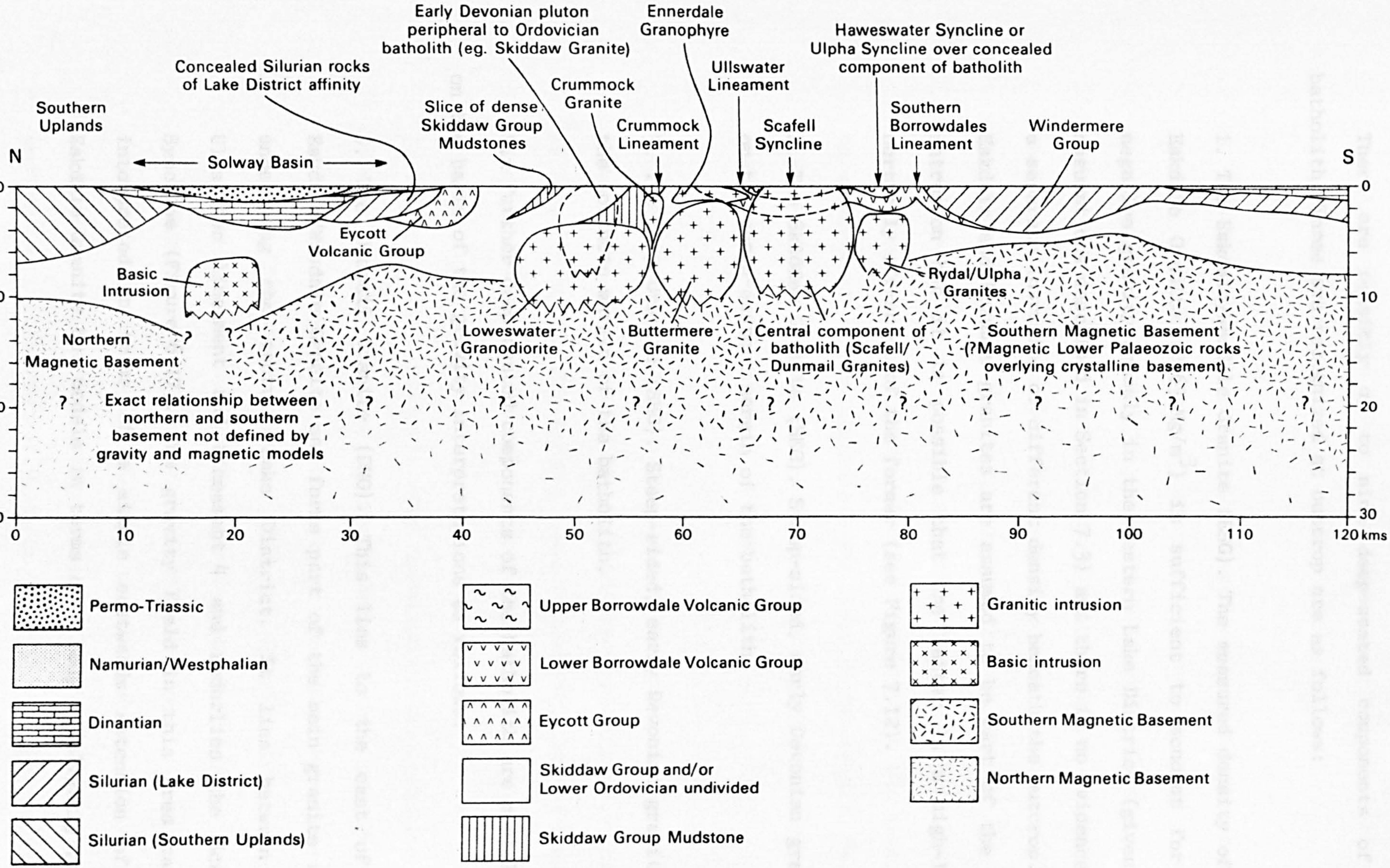

Figure 8.2 Schematic cross-section of the Lake District synthesized from the 2.5D models.

There are possibly up to nine deep-seated components of the batholith. Three are recognized at outcrop are as follows:

1. The Eskdale/Wasdale Granite (ESG). The measured density of the Eskdale Granite (2.63 Mg/m^3) is sufficient to account for the negative gravity anomaly in the western Lake District (given the assumptions described in Section 7.3) and there is no evidence for a separate intrusion of different density beneath the outcrop. The Eskdale and Wasdale granites are assumed to be part of the same intrusion but it is possible that the latter is a high-level northerly off-shoot of the former (see Figure 7.12).

2. The Skiddaw Granite (SKG). Steep-sided, early Devonian granite on the north-eastern margin of the batholith.

3. The Shap Granite (SHG). Steep-sided, early Devonian granite on the southern margin of the batholith.

Six further deep-seated components of the batholith are postulated on the basis of the gravity interpretations as follows:

4. The Dunmail Granite (DMG). This lies to the east of the Eskdale/Wasdale Granite and forms part of the main granite ridge underlying the central Lake District. It lies between the Ullswater lineament and Lineament 4 and underlies the Scafell Syncline (Figure 6.17). The gravity field in this area can be interpreted in terms of a simple eastwards extension of the Eskdale Granite but models in terms of a body of slightly higher

density (around 2.66 Mg/m^3) are considered to be marginally more realistic.

5. The Buttermere Granite (BMG). There is good evidence from the present work (Section 7.4, profile AB) and previous gravity interpretations (Bott 1974) that the Ennerdale Granophyre is underlain by an intrusion of somewhat higher density. The present interpretation has explained this in terms of a separate, major component of the batholith lying to the north of the Eskdale-Dunmail ridge, between the Crummock and Ullswater lines. A reasonable fit to the gravity field is obtained if the intrusion is assumed to extend to around the same depth as the Eskdale Granite (i.e. 9 km) and have a density between that of granite and granodiorite (i.e. around 2.68 Mg/m^3).

6. The Loweswater Granodiorite (LGD). A marginal component of the batholith of granodioritic composition (density around 2.70 Mg/m^3) is required to fit the gravity field to the north of the Crummock line but the form of the body is not well defined.

7. The Rydal Granite (RDG). This component of the batholith lies between lineaments 4 and 10 (see Figure 6.17) and underlies the south-western part of the Haweswater Syncline. An alternative interpretation of the gravity field is possible in terms of a thick sequence of low-density Upper Borrowdale volcanics above a south-easterly extending shoulder of the Dunmail Granite (see Section 7.10, profile YZ). However, an interpretation in terms of a separate component of the batholith of density between that of granite and granodiorite (i.e. around 2.68 Mg/m^3) is considered to

be more likely given the present understanding of the bulk density and thickness of the overlying volcanic sequence.

8. The Ulpha Granite (ULG). The gravity models indicate that the Eskdale Granodiorite and the Ulpha Syncline are underlain either by a granite shoulder extending southwards from the Eskdale Granite or a separate component of the batholith of slightly higher density than the Eskdale Granite (see Sections 7.4 and 7.7). Models based on a separate intrusion give a marginally better fit to the gravity data and recently reported high temperature mineralization at Black Combe (D.C. Cooper, BGS pers. comm.) supports the concept of a granitic intrusion rather than a marginal granodiorite.

9. The Haweswater Granite (HWG). The prominent gravity anomaly over the Haweswater Complex must be due to an underlying granitic pluton on the northern side of the Shap Granite. The intrusion cannot be distinguished from the latter in terms of density contrast but the lack of any corresponding magnetic anomaly suggests a separate intrusion rather than a subsurface continuation of the Shap Granite (see Section 7.12, profile GH). Figure 8.1 shows no eastwards extension towards the Weardale Granite but models in terms of a granite ridge beneath the Vale of Eden are possible, depending on the assumptions made for the thickness of the Silurian to Lower Carboniferous sequence within the vale (see Section 7.13, profile IJ).

A further three intrusions, which are recognized at outcrop, are interpreted as high-level intrusions of limited depth extent:

10. The Ennerdale Granophyre (ENG). Gravity modelling (this work and Bott 1974) suggests that the granophyre is only around 1 to 2 km thick and is underlain by an intrusion of higher density (the Buttermere Granite, see above). It extends in subcrop south-eastwards towards the Wasdale Granite. The underside of the granophyre is probably not in contact with the underlying Buttermere Granite along its northern margin. Magnetic anomalies over the granophyre are associated with rafts of magnetic hybrid rocks (microdiorite) within the intrusion.

11. The Eskdale Granodiorite (EGD). This can be interpreted either as a marginal granodioritic phase to the Eskdale Granite or a separate intrusion of laccolithic form underlain by the Ulpha Granite (see above). Even when interpreted as a body extending to depth on the southern margin of the Eskdale Granite, the northern half of the intrusion must be relatively thin (only 1 to 2 km thick) and underlain by granitic material (see Section 7.7, profile KL).

12. The Threlkeld Microgranite (TMG). The gravity models support the geological evidence that this is an irregular laccolith intruded into the Skiddaw Slates (Firman 1978). It lies along the Crummock line, over the north-eastern margin of the batholith. The intrusion is around 0.5 to 1 km thick and extends in subcrop over an area around three times that observed at outcrop (see Section 7.11, profile EF).

A further two concealed high-level intrusions are postulated on the basis of the gravity interpretations:

13. The Crummock Granite (CWG). There is strong evidence for a high-level granitic intrusion beneath the Crummock Water Aureole from both gravity modelling (Sections 7.4 to 7.9) and geochemical data (Cooper et al. 1988, supplementary paper S2). The models suggest an elongate intrusion, reaching to within around 0.5 km of the surface, along the northern margin of the Buttermere Granite (i.e. along the Crummock line).

14. The Coniston Granite (CNG). The prominent residual gravity low in the Coniston area can be modelled in terms of either high level granitic intrusion into the Borrowdale Volcanic Group, a low density sequence of Upper Borrowdale volcanics or a small deep-seated component of the batholith. The gravity field is not particularly well defined over the anomaly but the presence of a granitic intrusion above the south wall of the batholith is considered to be a reasonable possibility in view of the copper mineralization in the Coniston area (see Sections 7.5 and 7.9, profiles WX and CD).

8.2 LINEAMENTS, LOWER PALAEOZOIC STRUCTURES AND THE EVOLUTION OF THE BATHOLITH

Three important ENE-trending geophysical lineaments across the Lake District have been recognized, namely the Crummock, Ullswater and Southern Borrowdales lineaments (Figure 6.17). These can, tentatively, be traced across the Vale of Eden onto the western margin of the Alston Block. Even more tentatively, the Crummock and Southern Borrowdales lineaments can possibly be correlated farther east with the Ninety Fathom and Lunedale/Butterknowle faults respectively. Prominent NE-trending lineaments are also visible across the central and western Lake District.

The lineaments are visible as geophysical features because they correspond to one or more important density or magnetization contrasts within either the Lower Palaeozoic succession or the batholith. The Crummock lineament was active as an important structural feature from early Ordovician to early Devonian times. It was possibly initiated as an extensional fault during the early development of the Skiddaw Group basin and was subsequently reactivated by compression and/or strike-slip movement, and also acted as a focus for minor intrusions (see Section 6.6.1). It is likely that the Ullswater and Southern Borrowdales lines had a similar structural history but direct evidence is lacking as the Skiddaw Group is mostly concealed in the central and southern Lake District. The NE-trending lineaments are less extensive but still significant in terms of their relation to important structures within the batholith and Borrowdale Volcanic Group.

The present interpretation suggests that both the major components of the batholith and the broad synclines within the Borrowdale Volcanic Group developed between the major ENE- and NE-trending lineaments. This raises the question of whether the lineaments simply reflect these structures or whether they pre-date them. The importance of the Crummock line prior to the Borrowdale volcanicity suggests the latter. The ENE-trending lineaments appear to divide distinctive tracts within the Skiddaw Group; the Crummock line between the northern sequence and the Buttermere Formation (Webb & Cooper 1988, A.H. Cooper pers. comm.)

and the Ullswater line possibly between tracts of slightly different density (see interpretations in Section 7). The Southern Borrowdales line now marks the contact between the Borrowdale and Windermere groups but it also appears to define a line south of which the volcanic sequence thins rapidly. It would seem likely, therefore, that at least some of these lines represent fundamental fractures within the underlying basement which were initiated prior to the Borrowdale volcanism and which influenced the subsequent structural development of the Borrowdale Volcanic Group and the intrusive form of the batholith. The same lines were then probably reactivated during the Emsian/Acadian deformation which marked the final episode of Iapetus closure. Later deformation (Hercynian, Tertiary) has relatively little signature on the geophysical images. This is because the major density and susceptibility contrasts in the upper crust were established during the period up to the final closure of Iapetus and later deformation caused only superficial modification to the deep-seated structures.

The question as to whether the residual gravity lows associated with the BVG synclines represent distinct underlying components of the batholith or thicker accumulations of low-density volcanic rocks (or both) has been discussed above, and alternative interpretations given in Section 7. Whichever is the case, however, they are clearly important structures. The Scafell, Haweswater and Ulpha synclines, and associated Nan Bield and Wrynose anticlines were considered by Soper & Newman (1974) to be large-scale compressional folds initiated in the Ordovician. The Nan Bield Anticline was considered to be an en echelon continuation of the Wrynose Anticline which in turn shared a common limb with the Ulpha Syncline. More recently, Branney & Soper (1988) have disputed both this connection and an Ordovician compressional origin for the folds. They have suggested that much of the pre-Windermere Group deformation in the BVG is volcano-tectonic in origin, and that the Ulpha and Scafell synclines may have been initiated as synvolcanic folds associated with the foundering of the volcanic pile. In a similar vein, Millward & Johnson (in prep.) consider that the thickness and sedimentology of Phase 2 volcanics in the SW Lake District indicate deposition within basins that are thought to have been fault controlled. These comments are in line with the general observation that the BVG was emplaced largely in a subaerial environment and must have been associated with crustal subsidence for the volcanic edifice to have survived subsequent erosion (Branney 1988, Branney & Soper 1988).

It is possible that vertical movement influenced by the pre-existing NE- and ENE-trending lineaments may have initiated the synclines and anticlines in the Ordovician, leading to thicker accumulations of BVG in the synclines and/or the subsequent emplacement of late Ordovician (or early Silurian?) components of the batholith beneath them. Alternatively, it is possible that each was initiated as a volcano-tectonic sag over a separate component of an evolving Ordovician batholith, the position of the batholith components themselves being influenced by earlier structural trends.

The age and evolution of the batholith has been the subject of extended debate in recent years. The reader is referred to Firman & Lee (1986) and subsequent correspondence in the Geological Magazine for a review of the evidence (Firman & Lee 1987, Soper 1987, Webb et al. 1987, Soper et al. 1987a, Allen 1987, Moseley 1988). Copies of these papers are included in this thesis at Appendix 2 (papers S3 and S4). It should be noted that discussion of the form of the batholith by Firman & Lee was based on the generalized 3-D model described in Chapter 4 (i.e. prior to the image processing and detailed modelling described in Chapters 5 and 6).

The Eskdale Granite, Eskdale Granodiorite and the Ennerdale Granophyre have been dated at 429 +/-4 Ma, 428 +/-71 Ma and 420 +/-4 Ma respectively (Rundle 1979) and are now considered to represent the first episode of major intrusive activity in the Lake District. The second major intrusive phase occured after the early Devonian cleavage-forming deformation and is represented at outcrop by the Shap (393 +/-3 Ma, Wadge et al. 1978) and Skiddaw (399 +/-8 Ma, Rundle 1981) granites.

The dates of the earlier granites correspond to the Llandovery to Wenlock period on most timescales (e.g. McKerrow et al. 1985). However, geological evidence (see above cited references) and geochemical studies (O'Brien at al. 1985) indicate that the Threlkeld Microgranite (dated at 438 +/- 6, Rundle 1981) and the Ennerdale Granophyre are subvolcanic intrusions related to the Borrowdale volcanism, and thus of Ordovician age. The Eskdale Granite is geochemically more evolved than the BVG but has a less fractionated REE (rare earth element) pattern than the Early Devonian Shap and Skiddaw granites (O'Brien et al. 1985). The geological evidence that the Eskdale Granite was emplaced prior to the early-Devonian deformation (see above cited references) is compatible with the pattern of geochemical evolution, but exactly when (between the Ordovician and early Devonian) it was emplaced is more difficult to establish.

Soper et al. (1987a) argue that the Eskdale Granite is related to BVG pyroclastic deposits but represents a later, and more chemically evolved, magma. This model implies emplacement towards the end of the Borrowdale volcanism, before the Caradoc-Ashgill transgression, and further implies that the dates of all the 'early' granitic intrusions were reset in the Silurian. Alternatively, Webb et al. (1987) and D. Millward (pers. comm.) have suggested that the radiometric dates of the 'early' granites are substantially correct, and that they were emplaced in the early Silurian, prior to the rapid deepening of the Windermere Group basin in Wenlock times. Webb et al. (1987) suggest that the repeated passage of magmas through the crust during the eruption of the Borrowdale Volcanic Group may have produced a suitably annealed system of channelways to serve as sites for the rise of later intrusions, and this would presumably explain the spatial correlation between the broad synclines in the BVG and the granite components postulated in the present work.

A further possibility, which has been suggested by O'Brien et al. (1985), is that the early intrusions are underlain by a later, Devonian age batholith. They point out that the Eskdale, Shap and Skiddaw granites show a progressive evolution towards increasingly fractionated REE patterns with time. This trend is accompanied by an increase in the level of radioactive elements (U, Th and K) so that the Devonian granites (Shap and Skiddaw) have a higher heat production than the earlier intrusions. O'Brien et al. (1985) postulate that the culmination of this trend may have been the emplacement of a large, high heat production granite beneath the Lake District at the end of the Caledonian orogeny, and they cite the measured high heat flow values in support.

The depth extent, form and density of the deeper parts of the batholith are not sufficiently well constrained by the gravity models to rule out totally the presence of a late intrusion beneath the western Lake District. It is possible that the Eskdale Granite is thinner than the value of around 9 km indicated by the models, and is underlain by a later intrusion of similar, or slightly lower density (see Section 7.4). Likewise, the concealed components of the batholith beneath the central Lake District could also be of early Devonian age. However, the use by O'Brien et al. (1985) of the heat flow data in support of this hypothesis is misleading. High heat flow values have indeed been recorded on the early Devonian Shap and Skiddaw granites (Whieldon et al. 1984, Lee et al. 1984, Lee et al. 1987) but no measurements have been made in the central and western Lake District. It is, therefore, not valid to argue on the basis of the present heat flow data that these areas are underlain by a high heat production batholith.

If it can be firmly established that the broad synclinal structures within the BVG are underpinned by immediately post-BVG (or Silurian) granites, or that they were initiated as volcano-tectonic sags over components of a developing Ordovician batholith, then this would reinforce the case in favour of a predominantly early (Ordovician/Silurian) batholith. This 'early' batholith would thus comprise all the deep-seated components identified by the modelling, except the Shap, Skiddaw (and possibly Haweswater?) granites. These steep-sided, early Devonian plutons would then have been emplaced on the margins of the existing batholith, together with smaller, high-level intrusions along pre-existing lines of weakness (e.g. the Crummock Granite along the Crummock line and possibly the Coniston Granite on the southern margin of the batholith). Alternatively, if future studies show that the low density sequences within the Upper Borrowdale Volcanic Group are thicker than has been supposed, or that no relationship can be established between structures within the BVG and the underlying batholith, then the case for a batholith comprising several separate (Ordovician or Silurian) components would be weakened. The situation will, no doubt, gradually be resolved as the geological mapping programme advances over the central and eastern parts of the BVG outcrop, providing more detailed information on the structure and evolution of the volcanic pile. A heat flow borehole sited on the Eskdale Granite would also help to resolve the question of whether a high heat production granite lies concealed beneath the western Lake District.

8.3 REGIONAL STRUCTURE

The schematic cross-section shown in Figure 8.2 shows the main elements of upper crustal structure from the Southern Uplands to the south of the Lake District. It is not based on any one profile in particular but is intended to illustrate some of the more important conclusions of the modelling from all the profiles.

The magnetic basement is shown as reaching nearest to the surface beneath the Windermere Group in the southern Lake District, deepening northwards beneath the batholith and approaching nearer to the surface again along the northern margin. The present models were developed partly on the assumption that there could be a connection between the magnetic basement in the southern Lake District and the magnetite-bearing rocks of Arenig age encountered in the Beckermonds Scar borehole (i.e. that the source of the long wavelength anomaly is predominantly upper crustal). However, as explained in Chapter 7, a whole range of models for the magnetic basement is possible. For example, it is not necessary to have the basement in direct contact with the base of the batholith which need not, therefore, necessarily thin towards the south. It is possible to fit the long wavelength components of the magnetic field across the Lake District in terms of a magnetic basement extending from well within the upper crust almost to the base of the crust, or in terms of a basement entirely within the lower crust. A common feature of all the models, however, is that the magnetic basement continues northwards beneath the batholith. The basement probably lies nearer to the surface in the western Lake District and deepens towards the east.

The 'magnetic basement' as shown in the models could represent either (a) a thick layer of pre-Skiddaw Group (magnetic) sedimentary rocks extending down to the mid crust, (b) magnetic crystalline basement, which may have acted as a source for the magnetite observed at Beckermonds Scar, or (c) a combination of both (i.e. a thin layer of (magnetic) pre-Skiddaw Group sedimentary rocks overlying (magnetic) crystalline basement). Along the northern margin of the Lake District the 'magnetic basement' deepens beneath the Solway/Carlisle Basin. This occurs approximately along strike (ENE) from the northerly-dipping reflectors on the WINCH-2 line which have been correlated with the trace of the Iapetus suture (e.g. Beamish and Smythe, 1986; see Section 1.4 and Figure 1.14). It is tempting, therefore, to correlate the 'magnetic basement' as defined by the present modelling with the reflective crust to the south of the suture on the WINCH-2 line (or at least the upper part of it).

The non-reflective crust between the upper surface of the 'suture' and the base of the Solway/Carlisle Basin (Figure 1.14) was ascribed by Beamish & Smythe (1986) to Lower Palaeozoic rocks of velocity 5.5 to 5.7 km/sec. This region on the present models comprises a zone of non-magnetic rocks of density 2.78 Mg/m^3. This is equivalent to the Skiddaw Group of the Lake District in terms of density and susceptibilty values but could equally well be similar (Ordovician) sedimentary rocks of Southern Uplands affinity, or possibly some form of dense, non-magnetic 'crystalline basement' (c.f. the 6.15 km/sec basement detected at a depth of around 4 km beneath the Northumberland Trough and Irish Sea by Bott et al., 1985).

The fact that the magnetic basement lies closest to the surface beneath the thickest development of the Windermere Group suggests that the southern Lake District may have been a basement 'high' prior to (and possibly during?) the Borrowdale volcanicity. Firman & Lee (1986, supplementary paper S3) envisaged the late Caradocian transgression of the Coniston Limestone Group as occurring over an uplifted volcanic horst underpinned by the early batholith. However, as Branney & Soper (1988) pointed out, there must have been a substantial net downward displacement across the volcanic tract (north of the southern Borrowdales lineament?) to permit the preservation of several kilometres of volcanic rocks. Perhaps a basement high in the southern Lake District persisted until mid-Caradoc time (or even early-Silurian time, see discussion in previous section), after which the area subsided more rapidly than the volcanic edifice which was by that time underpinned by the Ordovician/Silurian batholith. However, if the magnetic basement corresponds to pre-Skiddaw Group rocks which extend at least to the mid-crust, this raises the question of whether the

Ordovician parts of the batholith were emplaced through the basement or whether the magnetic rocks were thrust beneath the Lake District during the final stages of Iapetus closure.

Features such as the complex Acadian thrust faulting which affects the Skiddaw Group are not well resolved by the models except, possibly, where they reactivate early extensional or strike-slip faults (e.g. the Causey Pike Thrust, along the Crummock line). On both the northern and southern margins of the Lake District, however, some models show structures which are compatible with the concept of late thrusts affecting the pre-Carboniferous basement. It is possible, for example, that the magnetic basement along the northern margin was brought nearer to the surface by southward-directed thrusts and similar northward-directed thrusts may have affected the basement on the southern margin.

The interpreted form of the Eycott Group along the northern margin of the Lake District indicates that the near-vertical lavas observed at outcrop flatten and thin northwards. On the north-eastern margin the sequence dips towards the ENE and does not extend south of the Crummock line.

The gravity models indicate that Silurian rocks may be preserved beneath the Carboniferous along the northern and north-eastern margins of the Lake District and possibly beneath the Vale of Eden. The Drygill Shales (Coniston Limestone Group), which occur in a small outlier on the northern edge of the Carrock Fell Complex, are the only remaining evidence at outcrop that an upper Ordovician - Silurian sequence once existed in the northern Lake District. However, Capewell (1955) noted that greywackes within the Lower Group of the Mell Fell Conglomerate matched perfectly with those of the Ludlow rocks of the southern Lake District (Brathay Flags and Coldwell Beds). He also noted that the size and little worn nature of the fragments made it unlikely that they were derived from the southern outcrop which in turn implied that a thick Silurian sequence must have been present on the northen side. The gravity models imply, however, that low-density Silurian rocks are absent or very thin beneath the Carlisle Basin. As explained in Chapter 7, this interpretation is critically dependent on the assumptions made regarding the background gravity field and the depth/density of the overlying Carboniferous - Triassic sequence. However, if correct it implies that the Silurian basin to the north of the Lake District was inverted by late Caledonian compression, partially eroded, then subsided again by reactivation of faults in extension in the Lower Carboniferous.

CHAPTER 9

OVERVIEW AND SUMMARY OF INVESTIGATIONS IN THE LAKE DISTRICT AND GEOTHERMAL STUDIES

9.1 GEOPHYSICAL INVESTIGATIONS IN THE LAKE DISTRICT

A total of 2213 new regional gravity observations have been made in the Lake District as part of the national coverage. These have been supplemented by 501 in-fill stations and 579 closely-spaced observations along traverses in the western Lake District. Between them, these surveys have defined the principal gravity anomalies in considerably more detail than previous widely-spaced observations. Physical property variations (mainly density) within the Lower Palaeozoic rocks of the Lake District have been studied in some detail from geophysical well logs and outcrop samples. Against this background, the gravity data, together with recently digitized aeromagnetic data, have been interpreted using a combination of image processing techniques and quantitative 2.5D and 3-D modelling. The study has led to a greatly improved understanding of structures within the Lower Palaeozoic sequences of the Lake District (principally the Skiddaw and Borrowdale Volcanic groups) and of the form and evolution of the composite granitic batholith.

The analysis of geophysical logs from the 300 m deep boreholes in the Shap and Skiddaw granites (and four granites in the Eastern Highlands of Scotland) has defined detailed physical property variations within the intrusions and led to a new appreciation of the response of logging tools in crystalline rocks. Prior to the present study, very little work had been carried out on the calibration and interpretation of commercial geophysical logs in granitic rocks (cf. McCann et al. 1982), especially in relation to the determination of geothermal properties and the effects of alteration. The responses of the logging tools have been evaluated in the six boreholes and logs of saturated density, heat production, conjectural lithology and rock condition have been derived by calibrating against the (short) cored sections of the boreholes.

Although the response of commercial logging equipment in crystalline rocks is still open to some conjecture, the logs have proved to be particularly effective for identifying changes in rock condition, lithology and physical properties between the short cored sections. The focussed electric logs are particularly sensitive to jointing and alteration, and have been used to estimate the proportion of altered and jointed rock in each borehole. The most severely altered and jointed sections are also characterized by low sonic velocity and high porosity. The imprint of alteration, however, often obscures more subtle variations due to changes in lithology. The geophysical logs have identified a surprisingly wide range of physical properties in what were thought to be fairly uniform granites. They have also shown that fresh, unaltered and unjointed granite is considerably less abundant than was thought. As well as defining detailed down-hole physical property variations, the study has provided well-constrained density values for subsequent gravity modelling. There is considerable scope for further research into the interpretation of geophysical logs in crystalline rocks, in particular into the use of cross-plots and correlations between different logs to identify, and distinguish between, joints, mineralized veins, different styles of alteration and lithological variations.

New density determinations have been made on rock samples from over 350 localities in the western and central Lake District in order to investigate density variations within the granite batholith and Lower Palaeozoic sequences. Samples have been classified in terms of their lithology and lithostratigraphy, and representative in-situ densities have been calculated for the principal formations. In addition to the density data, a small number of magnetic susceptibility and sonic velocity determinations were also carried out. Each of the main granitic intrusions is characterized by a slightly different density value but the data offer no convincing evidence for systematic density variations or zonation within each intrusion. Densities within the Borrowdale Volcanic Group vary widely with composition. Formations comprising mainly acid lavas and ignimbrites have values as low as 2.70 Mg/m^3 (e.g. the Airy's Bridge Formation) while those comprising basaltic lavas have values as high as 2.81 Mg/m^3 (e.g. the Ullswater Basalts). Within the Skiddaw Group, there is a significant contrast between the sandstone/greywacke and mudstone/siltstone lithologies (2.72 and up to 2.81 Mg/m^3 respectively). Density values for the Windermere Group, in the southern part of the Lake District, range from 2.69 Mg/m^3 (the Coniston Grit and Kirby Moor Flag formations) to 2.77 Mg/m^3 (the Browgill Beds).

The new determinations delineate density variations within the Lower Palaeozoic rocks of the Lake District in considerably more detail than previously published values, and provide a more secure basis for the interpretation of the gravity data. There is still considerable scope for extending the database, in particular to the Eycott Volcanic Group and the eastern parts of the Skiddaw and Borrowdale Volcanic groups. It cannot be overstressed, however, that such studies should be carried out in parallel with modern geological mapping in order to take account of the complexities of structural and lithological variations in the Lake District.

Image processing techniques have been used to analyse the gravity and aeromagnetic fields in the Lake District. A variety of techniques has been applied (and further developed) for enhancing residual anomalies and structural trends. The results have been related to both local geological structures and the structural evolution of the area. A particular objective has been to integrate the use of image analysis techniques with detailed quantitative modelling, rather than simply to identify anomalies and lineaments from the images, as is usually the case.

Three important ENE-trending geophysical lineaments across the Lake District (the Crummock, Ullswater and Southern Borrowdales lineaments) have been recognized from the gravity and magnetic images. Several prominent, but less extensive, NE-trending lineaments are also visible across the central and western Lake District. In addition to previously recognized gravity lows over the major granite outcrops, a number of residual lows have been identified where the batholth is concealed. These lows coincide approximately with the Scafell, Haweswater and Ulpha synclines in the Borrowdale Volcanic Group and lie between the major lineaments. The ENE-trending set of lineaments appear to divide distinctive tracts within the Skiddaw Group. This is particularly apparent in relation to the Crummock line, which was first recognized as a geophysical lineament from the present study and is now known to separate the northern and southern sequences of the Skiddaw

Group, and to be associated with faulting and intrusive activity from Arenig to early-Devonian times.

It seems likely that at least some of the lineaments represent fundamental fractures within the underlying basement which were initiated prior to the Borrowdale volcanism and which have influenced the subsequent structural development of the Borrowdale Volcanic Group and the intrusive form of the batholith. On a broader scale, gravity and magnetic images of northern England and the southern UK have help set the Lake District in its regional context. Outside the Lake District the images have been analysed only superficially. There is considerable scope for carrying out a more detailed analysis, especially in relation to the plate-tectonic evolution of the Iapetus Suture Zone.

Quantitative modelling of subsurface structures has been carried out in two stages. The first stage comprised a three-dimensional interpretation of the form of the granite batholith from regional gravity data, based on a simplified density distribution. The gravitational effects of the surrounding low density Permo-Triassic, Carboniferous and Silurian sedimentary successions were calculated and removed from the observed field. The remaining residual gravity field due to batholith was interpreted on a 1 km grid in terms of a generalized, two-density model extending to a depth of around 9 km. The interpretation confirms that the Skiddaw Granite is steep-sided relatively flat-topped intrusion. The roof zone encompasses the Grainsgill, Caldew and Sinnen Gill outcrops, and corresponds well with the mapped thermal aureole. Likewise, the upper roof region of the Shap Granite also coincides with the metamorphic aureole but a broad granite shoulder extends to the northwest, beneath the Haweswater Igneous Complex, which possibly represents a separate intrusion. In the central and western Lake District the model gives the generalized 3-D form of the batholith but does not take into account the undoubted composite nature of the body or the density variations within the Skiddaw and Borrowdale Volcanic groups.

The second stage of quantitative interpretation comprised joint gravity/magnetic modelling along a series of profiles, to examine structures on both local and regional scales. The models were based on the full physical property database, together with the tighter geological control provided by recent mapping and the additional structural insight provided by the image analysis.

The detailed modelling indicates that there may be up to fourteen identifiable (separate or related) granitic intrusions in the Lake District, some as deep-seated components of the batholith and others as high-level intrusions. There are possibly up to nine deep-seated components. The Eskdale/Wasdale Granite forms a major component of Ordovician or Silurian age in the western Lake District. The Shap and Skiddaw granites are steep-sided, early Devonian intrusions on the south-eastern and north-eastern margins of the batholith respectively. The residual gravity anomalies associated with the Scafell, Haweswater and Ulpha synclines are tentatively interpreted in terms of further separate batholith components but alternative interpratations in terms of thickened BVG sequences are also possible. Other separate components are postulated along the northern side of the batholith and beneath the Haweswater Complex. The Ennerdale Granophyre and Threlkeld Microgranite are modelled as high-level intrusions, in line with previous interpretations, and it posssible that Eskdale Granodiorite is also in this category. There is good evidence for a high-level granitic intrusion of early Devonian age beneath the Crummock aureole, and some evidence for a similar intrusion near Coniston.

The presence of residual gravity lows associated with the Scafell, Haweswater and Ulpha synclines suggests that these are structures of major significance, whether the lows represent thickened volcanic sequences or underlying batholith components, or both. It is possible that vertical movement influenced by the pre-existing NE- and ENE-trending lineaments may have initiated the synclines and anticlines in the Ordovician, leading to a thicker accumulation of BVG in the synclines and/or the subsequent emplacement of late Ordovician (or early Silurian?) components of the batholith beneath them. Alternatively, it is possible that each was initiated as a volcano-tectonic sag over a separate component of an evolving Ordovician batholith, the position of the batholith components themselves being influenced by earlier structural trends.

The age of the various components of the composite batholith continues to be the subject of heated debate. The present author is still of the view that the bulk of the western and concealed parts of the batholith are probably 'early' (i.e. of Ordovician or Silurian age), based on their apparent relationship with structures within the BVG and other evidence discussed in Chapter 8. The early Devonian Shap and Skiddaw granites were then emplaced as distinctly separate, steep-sided plutons on the margins of the early batholith, together with smaller high-level intrusions along pre-existing lines of weakness (e.g. the Crummock Granite). However, the existence of the Crummock

Granite points to the presence of intrusive activity in the western Lake District during early Devonian times, and the possibility of a concealed 'late' batholith cannot be ruled out.

On a broader scale, the modelling indicates that long wavelength magnetic anomalies are best interpreted as 'magnetic basement' which reaches nearest to the surface beneath the Windermere Group in the southern Lake District, deepens northwards beneath the batholith and approaches nearer to the surface again along the northern margin. This basement could represent either a thick layer of pre-Skiddaw Group (magnetic) sedimentary rocks extending down to the mid crust, magnetic crystalline basement, or a combination of both. Along the northern margin of the Lake District the 'magnetic basement' deepens beneath the Solway/carlisle Basin, the deepening occuring approximately along strike (ENE) from the northerly-dipping reflectors on the WINCH-2 line which have been correlated with the trace of the Iapetus Suture. Silurian rocks may lie concealed beneath the Carboniferous strata along the northern margin of the Lake District, but the shape of the gravity field in some areas could also be explained in terms of concealed, low density volcanic rocks related to the Eycott Volcanic Group.

Overall, the geophysical investigations described in this thesis have advanced the understanding of the deep geology of the Lake District in a number of directions. They have provided a more detailed understanding of the form and composition of the batholith, much greater knowledge of structures within the Lower Palaeozoic succession (and the influence of these on the gravity models), and an appreciation of the influence of structural controls on the evolution both of the batholith and of the Skiddaw and Borrowdale Volcanic groups. However, geological research in the Lake District is progressing at an extremely rapid pace. If changes over the past few years are anything to go by, further advances in the understanding of the development of the Skiddaw, Borrowdale and Eycott groups are to be expected. The present geophysical interpretations, in particular those aspects related to concealed components of the batholith, should be regarded as 'working models' to be tested and, if found wanting, modified.

9.2 GEOTHERMAL STUDIES AND THE RELATIONSHIP BETWEEN HEAT FLOW AND HEAT PRODUCTION IN THE UK

The geothermal characteristics and Hot Dry Rock (HRD) potential of Caledonian-age granites in the Lake District and Eastern Highlands of Scotland have been studied as part of a collaborative research programme between BGS, The Open University and Imperial College. Those elements of the work carried out personally by the author, and concerned specifically with the Lake District granites, have been described in the Chapters 3 and 4 of the thesis (i.e. the analysis of geophysical logs from the Shap and Skiddaw heat-flow boreholes and the 3-D gravity modelling respectively). The background to HDR exploration in the UK and details of the research programme as a whole (including the work carried out by the author's co-workers) are described fully in papers S5, S6 and S7 (see Appendix 3).

Heat flow measurements made by the Imperial College group (Wheildon et al. 1984a) give values of 78 and 101 mW/m^2 on the Shap and Skiddaw granites respectively. Together with a previously reported value of 95 mW/m^2 from the Weardale Granite (England et al. 1980), these define a high heat flow zone in northern England. Values from the Eastern Highlands granites range between 59 and 76 mW/m^2 (Wheildon et al. 1984b). These are lower than expected considering the high values of radiogenic heat production measured at outcrop and in the boreholes (Webb & Brown 1984b and Appendix 5 respectively). However, they are still well above the UK average and show that the Eastern Highlands batholith forms a high heat flow zone within Scotland. Numerical models of the heat flow in each area were generated by the Imperial College group (Wheildon et al. 1984 a & b) and the HDR potential of each intrusion was assessed on the basis of information from all the component parts of the programme. The results show that, while predicted sub-surface temperatures in the Lake District and Eastern Highlands granites are above those expected in surrounding basement rocks, their HDR geothermal potential is not as great as that in the Cornubian and Weardale batholiths (see supplementary paper S5, Lee 1986b, Appendix 3).

The most important conclusions to come out of the work, however, were related not to the HDR potential of the granites, but to the significance of the results in terms of the relationship between heat flow (q_0) and heat production (A_0) in the UK. Previous work in this field (see supplementary papers S6 and S7 in Appendix 3) had demonstrated an empirical relationship between surface heat flow (q_0) and surface heat production (A_0) in plutonic and metamorphic terrains in many parts of the world. The relationship takes the form:

$$q_0 = q^* + DA_0$$

where D is a function of the depth extent of the upper crustal zone of radioelement enrichment and q* represents the heat flow contribution from beneath this zone. Where the relationship is satisfied over large geographic areas, known as 'heat flow provinces, it is implied that q* and D are constants.

The new heat flow and heat production data for the Lake District and Eastern Highlands granites, together with previously published data for other UK granites and basement rocks (Table 1, paper S6) are plotted on a q_0-A_0 diagram in Figure 9.1. The diagram shows that the single linear correlation previously identified for southern Britain (Richardson & Oxburgh 1978, 1979; inset to Figure 9.1) is clearly not tenable for the UK as a whole. Closer examination of the q_0-A_0 diagram shows that the data form four separate clusters; three of which correspond to granite batholiths (in SW England, northern England and the Eastern Highlands of Scotland) and a fourth to the basement rocks of central England and Wales. Each of these areas has its own distinct tectonic and thermal history. An analysis in terms of two broad 'heat flow provinces' for southern and northern Britain (regression lines a and b, Figure 9.1) is, therefore, also considered to be inappropriate, on both geological and statistical grounds.

The availability from the geothermal programme of high quality heat flow and heat production measurements, together with models of the sub-surface form of the granite batholiths, enabled the project team to examine the factors affecting the q_0-A_0 relationship in more detail than had been possible in the past. This led to the proposition that the distribution of points is best explained in terms of separate 'thermo-tectonic provinces', which are each characterized by a distinct geological, tectonic and thermal history, but which cannot necessarily

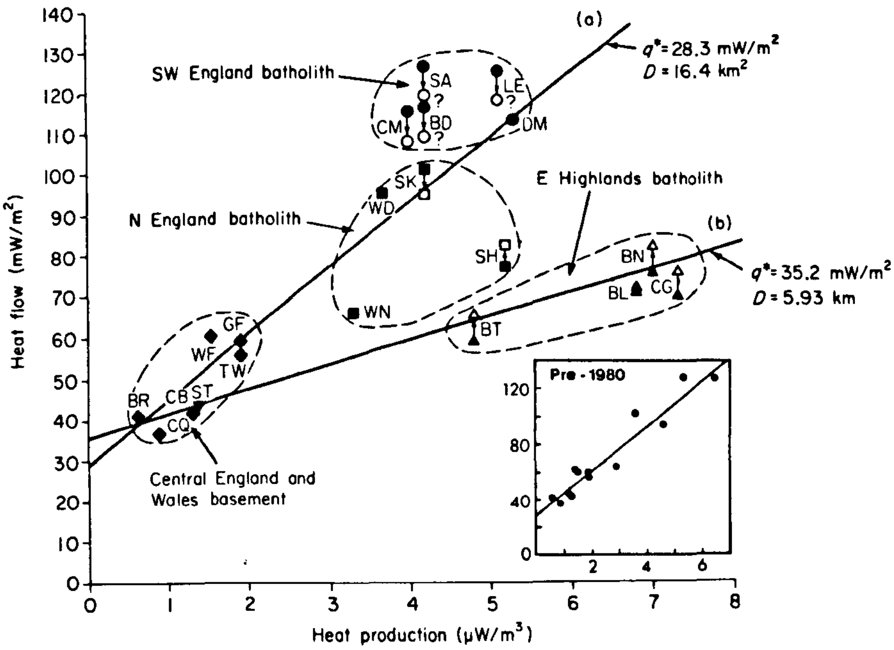

Figure 9.1 Plot of heat flow against heat production for UK granites and basement rocks compiled from the data listed in Table 1 of Lee et al. 1987. Solid symbols represent measured heat flow, open symbols represent the equivalent one-dimensional heat flow calculated from published models. Clusters of data points from specific areas are ringed. Line (a) is a linear regression of all the data from England and Wales, and line (b) is a linear regression of all the data from the Eastern Highlands and northern Scotland (both are based on the equivalent 1D heat flow values). D and q* are defined in the text. The inset shows the pre-1980 correlation (q* = 27 mW/m², D = 16.6 km, from Richardson & Oxburgh 1979). Codes identify granites and boreholes as follows: CM, Carnmenellis Granite; BD, Bodmin Granite; LE, Lands End Granite; SA, St Austell Granite; DM, Dartmoor Granite; WD, Weardale Granite; WN, Wensleydale Granite; SH, Shap Granite; SK, Skiddaw Granite; CG, Cairngorm Granite; BT, Mount Battock Granite; BL, Ballater Granite; BN, Bennachie Granite; ST, Strath Halladale Granite; CQ, Croft Quarry; BR, Bryn Teg; CB, Coed-y-Brenin; GF, Glanfred; TW, Thorpe-by-Water, WF, Withy Combe Farm.

be characterized by a linear q_0-A_0 relationship. Thus the cluster of q_0-A_0 points from the metavolcanic and metesedimentary basement of central England and Wales are consistent with a poorly radiothermal and relatively unfractionated upper crust in these areas, and cannot be incorporated with data from a batholith having a totally different history to define a 'regression line' representing a broad 'heat flow province' with characteristic values of q* and D.

The separate data clusters for the granite batholiths reflect their contrasting depth extent and radioelement - depth functions, which are in turn related to the the magmatic evolution and emplacement history of each batholith and the nature of the crust into which they were emplaced. The q_0-A_0 signatures of different intrusions within the same 'thermo-tectonic province' are likely to have more in common with each other than with granites from another province. However, some varitaion within a province, or even within a single composite batholith, might be expected because of local differences in emplacement history and magma source, and as a reflection of the evolution of the orogenic belt with time. Moreover, the q_0-A_0 signature of a granitic batholith need not necessarily be related to that of the surrounding basement rocks, which should reflect the pre-batholithic history of those rocks and their subsequent reworking during the evolution of the orogenic belt.

The overall outcome of this study has been completely to re-define the relationship between heat flow and heat production in the UK, from a simple linear correlation to a more complex pattern which reflects the geological and tectonic diversity between different regions.

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